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Hierarchical adaptive sparse grids and quasi Monte Carlo for option pricing under the rough Bergomi model

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Abstract

The rough Bergomi (rBergomi) model, introduced recently in [4], is a promising rough volatility model in quantitative finance. It is a parsimonious model depending on only three parameters, and yet exhibits remarkable fit to empirical implied volatility surfaces. In the absence of analytical European option pricing methods for the model, and due to the non-Markovian nature of the fractional driver, the prevalent option is to use the Monte Carlo (MC) simulation for pricing. Despite recent advances in the MC method in this context, pricing under the rBergomi model is still a time-consuming task. To overcome this issue, we design a novel, hierarchical approach, based on i) adaptive sparse grids quadrature (ASGQ), and ii) quasi Monte Carlo (QMC). Both techniques are coupled with Brownian bridge construction and Richardson extrapolation. By uncovering the available regularity, our hierarchical methods demonstrate substantial computational gains with respect to the standard MC method, when reaching a sufficiently small relative error tolerance in the price estimates across different parameter constellations, even for very small values of the Hurst parameter. Our work opens a new research direction in this field, i.e., to investigate the performance of methods other than Monte Carlo for pricing and calibrating under the rBergomi model.

1 Introduction

Modeling volatility to be stochastic, rather than deterministic as in the Black-Scholes model, enables quantitative analysts to explain certain phenomena observed in option price data, in particular the implied volatility smile. However, this family of models has a main drawback in failing to capture the true steepness of the implied volatility smile close to maturity. Jumps can be added to stock price models to overcome this undesired feature, for instance by modeling the stock price process as an exponential Lévy process. However, the addition of jumps to stock price processes remains controversial [14, 3].

Motivated by the statistical analysis of realized volatility by Gatheral, Jaisson and Rosenbaum [20] and the theoretical results on implied volatility [2, 18], rough stochastic volatility has emerged as a new paradigm in quantitative finance, overcoming the observed limitations of diffusive stochastic volatility models. In these models, the trajectories of the volatility have lower Hölder regularity than the trajectories of standard Brownian motion [4, 20]. In fact, they are based on fractional Brownian motion (fBm), which is a centered Gaussian process, whose covariance structure depends on the so-called Hurst parameter, H (we refer to [26, 16, 11] for more details regarding the fBm processes). In the rough volatility case, where $0 < H < 1/2$, the fBm has negatively correlated increments and rough sample paths. Gatheral, Jaisson, and Rosenbaum [20] empirically demonstrated the advantages of such models. For instance, they showed that the log-volatility in practice has a similar behavior to fBm with the Hurst exponent $H \approx 0.1$ at any reasonable time scale (see also [19]). These results were confirmed by Bennedsen, Lunde and Pakkanen [8], who studied over a thousand individual US equities and showed that H lies in $(0, 1/2)$ for each equity. Other works [8, 4, 20] showed further benefits of

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such rough volatility models over standard stochastic volatility models, in terms of explaining crucial phenomena observed in financial markets.

The rough Bergomi (rBergomi) model, proposed by Bayer, Friz and Gatheral [4], was one of the first developed rough volatility models. This model, depending on only three parameters, shows remarkable fit to empirical implied volatility surfaces. The construction of the rBergomi model was performed by moving from a physical to a pricing measure and by simulating prices under that model to fit the implied volatility surface well in the case of the S&P 500 index with few parameters. The model may be seen as a non-Markovian extension of the Bergomi variance curve model [10].

Despite the promising features of the rBergomi model, pricing and hedging under such a model still constitutes a challenging and time-consuming task due to the non-Markovian nature of the fractional driver. In fact, the standard numerical pricing methods, such as PDE discretization schemes, asymptotic expansions and transform methods, although efficient in the case of diffusion, are not easily carried over to the rough setting. Furthermore, due to the lack of Markovianity and affine structure, conventional analytical pricing methods do not apply. To the best of our knowledge, the only prevalent method for pricing options under such models is Monte Carlo (MC) simulation. In particular, recent advances in simulation methods for the rBergomi model and different variants of pricing methods based on MC under such a model have been proposed in [4, 5, 9, 28, 24]. For instance, in [28], the authors employ a novel composition of variance reduction methods. When pricing under the rBergomi model, they achieved substantial computational gains over the standard MC method. Greater analytical understanding of option pricing and implied volatility under this model has been achieved in [25, 17, 6]. It is crucial to note that hierarchical variance reduction methods, such as Multi-level Monte Carlo (MLMC), are inefficient in this context, because of the poor behavior of the strong error, that is of the order of H [31].

Despite recent advances in the MC method, pricing under the rBergomi model is still computationally expensive. To overcome this issue, we design novel fast option pricers for options whose underlyings follow the rBergomi model, based on i) adaptive sparse grids quadrature (ASGQ), and ii) quasi Monte Carlo (QMC). Both techniques are coupled with Brownian bridge construction and Richardson extrapolation. To use these two deterministic quadrature techniques (ASGQ and QMC) for our purposes, we solve two main issues that constitute the two stages of our newly designed method. In the first stage, we smoothen the integrand by using the conditional expectation, as was proposed in [34] in the context of Markovian stochastic volatility models, and in [7] in the context of basket options. In a second stage, we apply the deterministic quadrature method, to solve the integration problem. In this stage, we apply two hierarchical representations before using the ASGQ or QMC method, to overcome the issue of facing a high-dimensional integrand due to the discretization scheme used for simulating the rBergomi dynamics. Given that ASGQ and QMC benefit from anisotropy, the first representation consists of applying a hierarchical path generation method, based on Brownian bridge (Bb) construction, with the aim of reducing the effective dimension. The second technique consists of applying Richardson extrapolation to reduce the bias, which in turn reduces the number of time steps needed in the coarsest level to achieve a certain error tolerance and consequently the maximum number of dimensions needed for the integration problem. We emphasize that we are interested in the pre-asymptotic regime (corresponding to a small number of time steps), and the use of Richardson extrapolation is justified by conjecture 3.1 and our observed experimental results in that regime, which suggest, in particular, that we have convergence of order one for the weak error and that the pre-asymptotic regime is enough to achieve sufficiently accurate estimates for the option prices. Furthermore, we emphasize that no proper weak error analysis has been performed in the rough volatility context.

Our first contribution is that we design a novel alternative approach based on a deterministic quadra-

ture, in contrast to the aforementioned studies such as [28]. Given that the only prevalent option in this context is to use different variants of the MC method, our work opens a new research direction in this field, i.e., to investigate the performance of methods other than MC for pricing and calibrating under the rBergomi model. Our second contribution is that we reduce the computational cost through bias reduction by using Richardson extrapolation. Finally, assuming one targets price estimates with a sufficiently small relative error tolerance, our proposed method demonstrates substantial computational gains over the standard MC method, even for very small values of H. We show these gains through our numerical experiments for different parameter constellations. However, we do not claim that these gains will hold in the asymptotic regime, which requires higher accuracy. Furthermore, in this work, we limit ourselves to comparing our novel proposed methods against the standard MC. A more systematic comparison with the variant of MC proposed in [28] is left for future research.

The outline of this paper is as follows: We begin in Section 2 by introducing the pricing framework that we are considering in this study. We provide some details about the rBergomi model, option pricing under this model and the simulation schemes used to simulate asset prices following the rBergomi dynamics. We also explain how we choose the optimal simulation scheme for an optimal performance of our approach. In Section 3, we discuss the weak error in the context of the rBergomi. Then, in Section 4 we explain the different building blocks that constitute our proposed methods, which are basically ASGQ, QMC, Brownian bridge construction, and Richardson extrapolation. Finally, in Section 5 we show the results obtained through the different numerical experiments conducted across different parameter constellations for the rBergomi model. The reported results show the promising potential of our proposed methods in this context.

2 Problem setting

In this section, we introduce the pricing framework that we consider in this work. We start by giving some details on the rBergomi model proposed in [4]. We then derive the formula of the price of a European call option under the rBergomi model in Section 2.2. Finally, we explain some details about the schemes that we use to simulate the dynamics of asset prices under the rBergomi model.

2.1 The rBergomi model

We consider the rBergomi model for the price process S_t as defined in [4], normalized to $r = 0$ (r is the interest rate), which is defined by

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

where the Hurst parameter $0 < H < 1/2$ and $\eta > 0$. We refer to v_t as the variance process, and $\xi_0(t) = \mathrm{E}[v_t]$ is the forward variance curve. Here, $\widetilde{W}^H$ is a certain Riemann-Liouville fBm process [27, 33], defined by

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

where the kernel $K^H : \mathbb{R}_+ \to \mathbb{R}_+$ is

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

By construction, $\widetilde{W}^H$ is a centered, locally $(H-\epsilon)$- Hölder continuous Gaussian process with Var $\left[\widetilde{W}_t^H\right] = t^{2H}$, and a dependence structure defined by

$$\mathrm{E}\left[\widetilde{W}_u^H \widetilde{W}_v^H\right] = u^{2H} G\left(\frac{v}{u}\right), \quad v > u,$$

where for $x \ge 1$ and $\gamma = \frac{1}{2} - H$

$$G(x) = 2H \int_0^1 \frac{ds}{(1-s)^\gamma (x-s)^\gamma}.$$

In (2.1) and (2.2), W^1, Z denote two *correlated* standard Brownian motions with correlation $\rho \in]-1, 0]$, so that we can represent Z in terms of W^1 as

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

where $(W^1, W^\perp)$ are two independent standard Brownian motions. Therefore, the solution to (2.1), with $S(0) = S_0$, can be written as

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

Remark 2.1. The rBergomi model is non-Markovian in the instantaneous variance v_t, that is $E\left[v_u \mid \mathcal{F}_t\right] \neq E\left[v_u \mid v_t\right]$. However, it is Markovian in the state vector by definition, that is $E\left[v_u \mid \mathcal{F}_t\right] = \xi_t(u)$.

2.2 Option pricing under the rBergomi model

We are interested in pricing European call options under the rBergomi model. Assuming $S_0 = 1$, and using the conditioning argument on the σ-algebra generated by W^1 (an argument first used by [34] in the context of Markovian stochastic volatility models), we can show that the call price is given by

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

where $C_{\mathsf{BS}}(S_0, k, \sigma^2)$ denotes the Black-Scholes call price, for initial spot price S_0, strike price k and volatility σ^2.

We point out that the analytical smoothing, based on conditioning, performed in (2.4) enables us to uncover the available regularity, and hence get a smooth, analytic integrand inside the expectation. Therefore, applying a deterministic quadrature technique such as ASGQ or QMC becomes an adequate option for computing the call price, as we will investigate later. A similar conditioning was used in [28] but for variance reduction purposes only.

2.3 Simulation of the rBergomi model

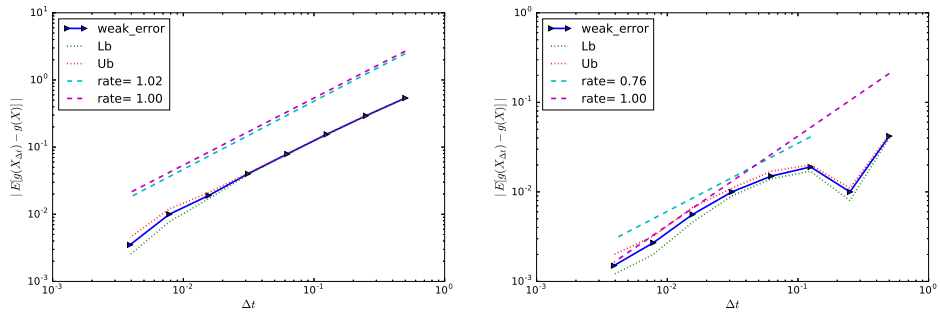
One of the numerical challenges encountered in the simulation of rBergomi dynamics is the computation of $\int_0^T \sqrt{v_t} dW_t^1$ and $V = \int_0^T v_t dt$ in (2.4), mainly because of the singularity of the Volterra kernel $K^H(s-t)$ at the diagonal $s = t$. In fact, one needs to jointly simulate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

i) **Covariance based approach (exact simulation) [4, 6]**: $W_{t_1}^1, \ldots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \ldots, \widetilde{W}_{t_N}$ together form a $(2N)$-dimensional Gaussian random vector with a computable covariance matrix, and therefore one can use Cholesky decomposition of the covariance matrix to produce exact samples of $W_{t_1}^1, \ldots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \ldots, \widetilde{W}_{t_N}$ from $2N$-dimensional Gaussian random vector as input. This method is exact but slow. The simulation requires $\mathcal{O}(N^2)$ flops. Note that the offline cost is $\mathcal{O}(N^3)$ flops.

ii) **The hybrid scheme of [9]**: This scheme uses a different approach, which is essentially based on Euler discretization but is 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 $W_{t_1}^1, \ldots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \ldots, \widetilde{W}_{t_N}$. However they are much more accurate than the samples produced from simple Euler discretization, but much faster than method (i). As in method (i), in this case, we need a $2N$-dimensional Gaussian random input vector to produce one sample of $W_{t_1}^1, \ldots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \ldots, \widetilde{W}_{t_N}$.

2.3.1 On the choice of the simulation scheme in our approach

The choice of the simulation scheme in our approach was based on the observed behavior of the weak rates. Through our numerical experiments (see Table 5.1 for the tested examples), we observe that although the hybrid and exact schemes seem to converge asymptotically with weak error of order $\mathcal{O}(\Delta t)$, the pre-asymptotic behavior of the weak rate is different for both schemes (we provide a short discussion of the weak error in Section 3). As an illustration, from Figure 2.1 for Set 1 parameter in Table 5.1, the hybrid scheme has a consistent convergence behavior in the sense that it behaves in an asymptotic manner basically right from the beginning, whereas the exact scheme does not. On the other hand, the constant seems to be considerably smaller for the exact scheme. These two features make the hybrid scheme the better choice to work with in our context since our approach is based on hierarchical representations involving the use of Richardson extrapolation (see Section 4.4).



(a) (b)

Figure 2.1: The convergence of the weak error $\mathcal{E}_B$, defined in (3.1), using MC with 6×10^6 samples, for Set 1 parameter in Table 5.1. We refer to C_{RB} (as in (2.4)) for $\mathrm{E}\left[g(X)\right]$, and to C^N_{RB} (as in (4.1)) for $\mathrm{E}\left[g(X_{\Delta t})\right]$. The upper and lower bounds are 95% confidence intervals. a) With the hybrid scheme b) With the exact scheme.

2.3.2 The hybrid scheme

As motivated in Section 2.3.1, in this work we use the hybrid scheme, which, on an equidistant grid $\{0, \frac{1}{N}, \frac{2}{N}, \ldots, \frac{NT}{N}\}$, is given by the following,

(2.5)
$$\widetilde{W}^H_{\frac{i}{N}} \approx \overline{W}^H_{\frac{i}{N}} = \sqrt{2H}\left(\sum_{k=1}^{\min(i,\kappa)} \int_{\frac{i}{N}-\frac{k}{N}}^{\frac{i}{N}-\frac{k}{N}+\frac{1}{N}} \left(\frac{i}{N}-s\right)^{H-1/2} dW^1_s + \sum_{k=\kappa+1}^{i} \left(\frac{b_k}{N}\right)^{H-1/2} \int_{\frac{i}{N}-\frac{k}{N}}^{\frac{i}{N}-\frac{k}{N}+\frac{1}{N}} dW^1_s\right),$$

which results for $\kappa = 1$ in (2.6).

(2.6)
$$\widetilde{W}^H_{\frac{i}{N}} \approx \overline{W}^H_{\frac{i}{N}} = \sqrt{2H}\left(W^2_i + \sum_{k=2}^{i} \left(\frac{b_k}{N}\right)^{H-\frac{1}{2}} \left(W^1_{\frac{i-(k-1)}{N}} - W^1_{\frac{i-k}{N}}\right)\right),$$

where N is the number of time steps and

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

The sum in (2.6) requires the most computational effort in the simulation. Given that (2.6) can be seen as discrete convolution (see [9]), we employ the fast Fourier transform to evaluate it, which results in $\mathcal{O}\left(N \log N\right)$ floating point operations.

We note that the variates $\overline{W}^H_0, \overline{W}^H_1, \ldots, \overline{W}^H_{\frac{[Nt]}{N}}$ are generated by sampling $[Nt]$ i.i.d draws from a $(\kappa+1)$-dimensional Gaussian distribution and computing a discrete convolution. We denote these pairs of Gaussian random variables from now on by $(\mathbf{W}^{(1)}, \mathbf{W}^{(2)})$.

3 Weak error discussion

To the best of our knowledge, no proper weak error analysis has been done in the rough volatility context. However, we try in this Section to shortly discuss it in the context of the rBergomi model.

In this work, we are interested in approximating $\mathrm{E}\left[g(X_T)\right]$, where g is some smooth function and X is the asset price under the rBergomi dynamics such that $X_t = X_t(W^{(1)}_{[0,t]}, \widetilde{W}_{[0,t]})$, where $W^{(1)}$ is standard Brownian motion and $\widetilde{W}$ is the fractional Brownian motion as given by (2.2). Then we can express the approximation of $\mathrm{E}\left[g(X_T)\right]$ using the hybrid and exact schemes as the following

$$\mathrm{E}\left[g\left(X_T\left(W^{(1)}_{[0,T]}, \widetilde{W}_{[0,T]}\right)\right)\right] \approx \mathrm{E}\left[g\left(\overline{X}_N\left(W^{(1)}_1, \ldots, W^{(1)}_N, \overline{W}_1, \ldots, \overline{W}_N\right)\right)\right] \quad \textbf{(Hybrid scheme)},$$

$$\mathrm{E}\left[g\left(X_T\left(W^{(1)}_{[0,T]}, \widetilde{W}_{[0,T]}\right)\right)\right] \approx \mathrm{E}\left[g\left(\overline{X}_N\left(W^{(1)}_1, \ldots, W^{(1)}_N, \widetilde{W}_1, \ldots, \widetilde{W}_N\right)\right)\right] \quad \textbf{(Exact scheme)},$$

where $\overline{W}$ is the approximation of $\widetilde{W}$ as given by (2.5) and $\overline{X}_N$ is the approximation of X using N time steps. In the following, to simplify notation, let $\overline{\mathbf{W}} = (\overline{W}_1, \ldots, \overline{W}_N)$, $\mathbf{W}^1 = (W^{(1)}_1, \ldots, W^{(1)}_N)$ and $\widetilde{\mathbf{W}} = (\widetilde{W}_1, \ldots, \widetilde{W}_N)$. Then, the use of Richardson extrapolation in our methodology presented in Section 4 is mainly justified by the conjecture 3.1.

Conjecture 3.1. *If we denote by $\mathcal{E}_B^{Hyb}$ and $\mathcal{E}_B^{Chol}$ the weak errors produced by the hybrid and Cholesky scheme respectively, then we have*

$$\begin{aligned}
\mathcal{E}_B^{Hyb} &= \left|\mathrm{E}\left[g\left(X_T\left(W^{(1)}_{[0,T]}, \widetilde{W}_{[0,T]}\right)\right)\right] - \mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \overline{\mathbf{W}}\right)\right)\right]\right| \\
&\leq \left|\mathrm{E}\left[g\left(X_T\left(W^{(1)}_{[0,T]}, \widetilde{W}_{[0,T]}\right)\right)\right] - \mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \widetilde{\mathbf{W}}\right)\right)\right]\right| + \\
&\quad + \left|\mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \overline{\mathbf{W}}\right)\right)\right] - \mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \widetilde{\mathbf{W}}\right)\right)\right]\right| \\
&\leq \mathcal{E}_B^{Chol} + \left|\mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \overline{\mathbf{W}}\right)\right)\right] - \mathrm{E}\left[g\left(\overline{X}_N\left(\mathbf{W}^1, \widetilde{\mathbf{W}}\right)\right)\right]\right|. \qquad (3.1)
\end{aligned}$$

From the construction of the Cholesky scheme, we expect that the weak error is purely the discretization error, that is

$$\mathcal{E}_B^{Chol} = \mathcal{O}\left(\Delta t\right),$$

as it was observed by our numerical experiments (for illustration see Figure 2.1b for the case of Set 1 *in Table 5.1). The second term in the right-hand side of* (3.1) *is basically related to approximating the integral* (2.2) *by* (2.6)*. From our numerical experiments it seems that this term is at least of order Δt and its rate of convergence is independent of H (for illustration see Figure 2.1a for the case of Set* 1 *in Table 5.1).*

4 Details of our hierarchical methods

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

- $\mathbf{W}^{(1)} = \{W^{(1)}_i\}_{i=1}^N$: The N Gaussian random variables that are defined in Section 2.1.
- $\mathbf{W}^{(2)} = \{W^{(2)}_j\}_{j=1}^N$: An artificially introduced N Gaussian random variables that are used for left-rule points in the hybrid scheme, as explained in Section 2.3.

We can rewrite (2.4) as

$$
\begin{aligned}
C_{\text{RB}}(T,K) &= \mathsf{E}\left[C_{\text{BS}}\left(S_0 = \exp\left(\rho\int_0^T \sqrt{v_t}dW_t^1 - \frac{1}{2}\rho^2\int_0^T v_t dt\right),\ k=K,\ \sigma^2 = (1-\rho^2)\int_0^T v_t dt\right)\right] \\
&\approx \int_{\mathbb{R}^{2N}} C_{BS}\left(G(\mathbf{w}^{(1)},\mathbf{w}^{(2)})\right)\rho_N(\mathbf{w}^{(1)})\rho_N(\mathbf{w}^{(2)})d\mathbf{w}^{(1)}d\mathbf{w}^{(2)} \\
&:= C_{RB}^N,
\end{aligned}
\tag{4.1}
$$

where G maps $2N$ independent standard Gaussian random inputs to the parameters fed to Black-Scholes formula, 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 (4.1) is based on hierarchical deterministic quadratures, namely i) ASGQ using the same construction in [22] and ii) randomized QMC based on lattice rules. We describe the ASGQ method in our context in Section 4.1, and in Section 4.2 we provide details on the implented QMC method. To make an effective use of either the ASGQ or the QMC method, we apply two techniques to overcome the issue of facing a high dimensional integrand due to the discretization scheme used for simulating the rBergomi dynamics. The first 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 4.3. The second technique 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 4.4.

If we denote by $\mathcal{E}_{\text{tot}}$ the total error of approximating the expectation in (2.4) using the ASGQ estimator, Q_N, then we have a natural error decomposition

$$\mathcal{E}_{\text{tot}} \leq \left|C_{\text{RB}} - C_{\text{RB}}^N\right| + \left|C_{\text{RB}}^N - Q_N\right| \leq \mathcal{E}_B(N) + \mathcal{E}_Q(\text{TOL}_{\text{ASGQ}}, N), \tag{4.2}$$

where $\mathcal{E}_Q$ is the quadrature error, $\mathcal{E}_B$ is the bias, TOL_{ASGQ} is a user selected tolerance for the ASGQ method, and C_{RB}^N is the biased price computed with N time steps as given by (4.1).

On the other hand, the total error of approximating the expectation in (2.4) using the randomized QMC or MC estimator, $Q_N^{\text{MC(QMC)}}$ can be bounded by

$$\mathcal{E}_{\text{tot}} \leq \left|C_{\text{RB}} - C_{\text{RB}}^N\right| + \left|C_{\text{RB}}^N - Q_N^{\text{MC (QMC)}}\right| \leq \mathcal{E}_B(N) + \mathcal{E}_S(M,N), \tag{4.3}$$

where $\mathcal{E}_S$ is the statistical error[1], M is the number of samples used for the MC or the randomized QMC method.

[1]The statistical error estimate of MC or randomized QMC is $C_\alpha \frac{\sigma_M}{\sqrt{M}}$, where M is the number of samples and $C_\alpha = 1.96$ for 95% confidence interval.

4.1 Adaptive sparse grids quadrature (ASGQ)

We assume that we want to approximate the expected value $\mathrm{E}[f(Y)]$ of an analytic function $f\colon \Gamma \to \mathbb{R}$ using a tensorization of quadrature formulas over Γ.

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

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

In our case, we have in (4.1) a multi-variate integration problem with, $f = C_{\mathsf{BS}} \circ G$, $\mathbf{Y} = (\mathbf{W}^{(1)}, \mathbf{W}^{(2)})$, and $\Gamma = \mathbb{R}^{2N}$, in the previous notations. Furthermore, since we are dealing with Gaussian densities, using Gauss-Hermite quadrature points is the appropriate choice.

We define for any multi-index $\boldsymbol{\beta} \in \mathbb{N}^{2N}$

$$Q^{m(\boldsymbol{\beta})} : C^0(\mathbb{R}^{2N}) \to \mathbb{R}, \quad Q^{m(\boldsymbol{\beta})} = \bigotimes_{n=1}^{2N} Q^{m(\beta_n)},$$

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

$$Q^{m(\boldsymbol{\beta})}[f] = \sum_{j=1}^{\#\mathcal{T}^{m(\boldsymbol{\beta})}} f(\widehat{y}_j)\overline{\omega}_j,$$

where $\widehat{y}_j \in \mathcal{T}^{m(\boldsymbol{\beta})}$ and $\overline{\omega}_j$ are products of weights of the univariate quadrature rules. To simplify notation, hereafter, we replace $Q^{m(\boldsymbol{\beta})}$ by $Q^{\boldsymbol{\beta}}$.

A direct approximation $\mathrm{E}\left[f[\mathbf{Y}]\right] \approx Q^{\boldsymbol{\beta}}[f]$ is not an appropriate option due to the well-known "curse of dimensionality". We use a hierarchical ASGQ[2] strategy, specifically using the same construction as in [22], and which uses stochastic discretizations and a classic sparsification approach to obtain an effective approximation scheme for $\mathrm{E}\left[f\right]$.

To be concrete, in our setting, we are left with a $2N$-dimensional Gaussian random input, which is chosen independently, resulting in $2N$ numerical parameters for ASGQ, which we use as the basis of the multi-index construction. For a multi-index $\boldsymbol{\beta} = (\beta_n)_{n=1}^{2N} \in \mathbb{N}^{2N}$, we denote by $Q_N^{\boldsymbol{\beta}}$ the result of approximating (4.1) with a number of quadrature points in the i-th dimension equal to $m(\beta_i)$. We further define the set of differences $\Delta Q_N^{\boldsymbol{\beta}}$ as follows: for a single index $1 \leq i \leq 2N$, let

$$\Delta_i Q_N^{\boldsymbol{\beta}} = \begin{cases} Q_N^{\boldsymbol{\beta}} - Q_N^{\boldsymbol{\beta}'}, \text{ with } \boldsymbol{\beta}' = \boldsymbol{\beta} - e_i, \text{ if } \boldsymbol{\beta}_i > 0, \\ Q_N^{\boldsymbol{\beta}}, \quad \text{otherwise,} \end{cases}$$

where e_i denotes the ith $2N$-dimensional unit vector. Then, $\Delta Q_N^{\boldsymbol{\beta}}$ is defined as

$$\Delta Q_N^{\boldsymbol{\beta}} = \left(\prod_{i=1}^{2N} \Delta_i\right) Q_N^{\boldsymbol{\beta}}.$$

[2] More details about sparse grids can be found in [12].

For instance, when $N = 1$, then

$$\Delta Q_1^{\boldsymbol{\beta}} = \Delta_2 \Delta_1 Q_1^{(\beta_1,\beta_2)} = \Delta_2 \left(Q_1^{(\beta_1,\beta_2)} - Q_1^{(\beta_1-1,\beta_2)} \right) = \Delta_2 Q_1^{(\beta_1,\beta_2)} - \Delta_2 Q_1^{(\beta_1-1,\beta_2)}$$
$$= Q_1^{(\beta_1,\beta_2)} - Q_1^{(\beta_1,\beta_2-1)} - Q_1^{(\beta_1-1,\beta_2)} + Q_1^{(\beta_1-1,\beta_2-1)}.$$

Given the definition of C_{RB}^N by (4.1), we have the telescoping property

$$C_{RB}^N = Q_N^\infty = \sum_{\beta_1=0}^{\infty} \cdots \sum_{\beta_{2N}=0}^{\infty} \Delta Q_N^{(\beta_1,\ldots,\beta_{2N})} = \sum_{\boldsymbol{\beta}\in\mathbb{N}^{2N}} \Delta Q_N^{\boldsymbol{\beta}}.$$

The ASGQ estimator used for approximating (4.1), and using a set of multi-indices $\mathcal{I} \subset \mathbb{N}^{2N}$ is given by

$$Q_N^{\mathcal{I}} = \sum_{\boldsymbol{\beta}\in\mathcal{I}} \Delta Q_N^{\boldsymbol{\beta}}. \tag{4.4}$$

The quadrature error in this case is given by

$$\mathcal{E}_Q(\mathrm{TOL}_{\mathrm{ASGQ}}, N) = \left| Q_N^\infty - Q_N^{\mathcal{I}} \right| \leq \sum_{\boldsymbol{\beta}\in\mathbb{N}^{2N}\setminus\mathcal{I}} \left| \Delta Q_N^{\boldsymbol{\beta}} \right|. \tag{4.5}$$

We define the work contribution, $\Delta\mathcal{W}_{\boldsymbol{\beta}}$, to be the computational cost required to add $\Delta Q_N^{\boldsymbol{\beta}}$ to $Q_N^{\mathcal{I}}$, and the error contribution, $\Delta E_{\boldsymbol{\beta}}$, to be a measure of how much the quadrature error, defined in (4.5), would decrease once $\Delta Q_N^{\boldsymbol{\beta}}$ has been added to $Q_N^{\mathcal{I}}$, that is

$$\Delta E_{\boldsymbol{\beta}} = \left| Q_N^{\mathcal{I}\cup\{\boldsymbol{\beta}\}} - Q_N^{\mathcal{I}} \right| \tag{4.6}$$

$$\Delta\mathcal{W}_{\boldsymbol{\beta}} = \mathrm{Work}[Q_N^{\mathcal{I}\cup\{\boldsymbol{\beta}\}}] - \mathrm{Work}[Q_N^{\mathcal{I}}]. \tag{4.7}$$

The construction of the optimal $\mathcal{I}$ is done by profit thresholding (see Figure 4.1 for illustration), that is, for a certain threshold value $\overline{T}$, and a profit of a hierarchical surplus defined by

$$P_{\boldsymbol{\beta}} = \frac{|\Delta E_{\boldsymbol{\beta}}|}{\Delta\mathcal{W}_{\boldsymbol{\beta}}},$$

the optimal index set $\mathcal{I}$ for our ASGQ is given by $\mathcal{I} = \{\boldsymbol{\beta} : P_{\boldsymbol{\beta}} \geq \overline{T}\}$.

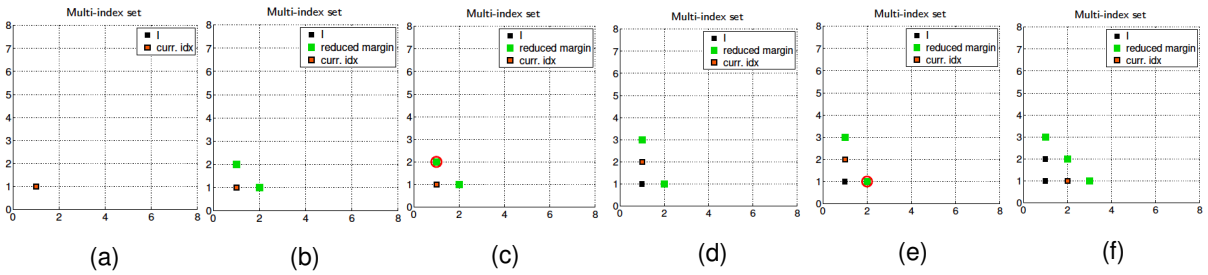
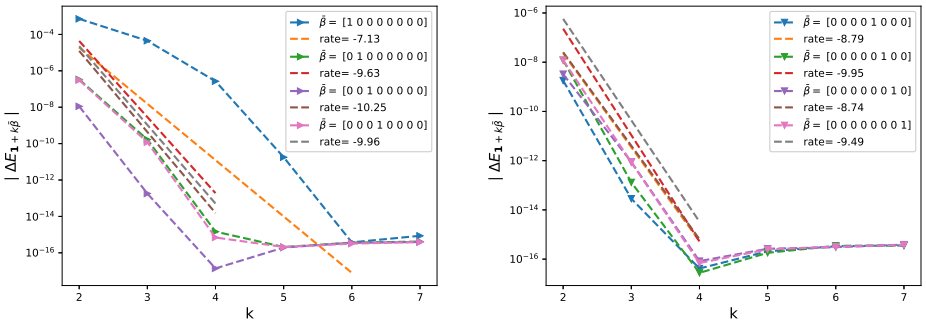


Figure 4.1: Construction of the index set for ASGQ method. A posteriori, adaptive construction: Given an index set $\mathcal{I}_k$, compute the profits of the neighbor indices and select the most profitable one.

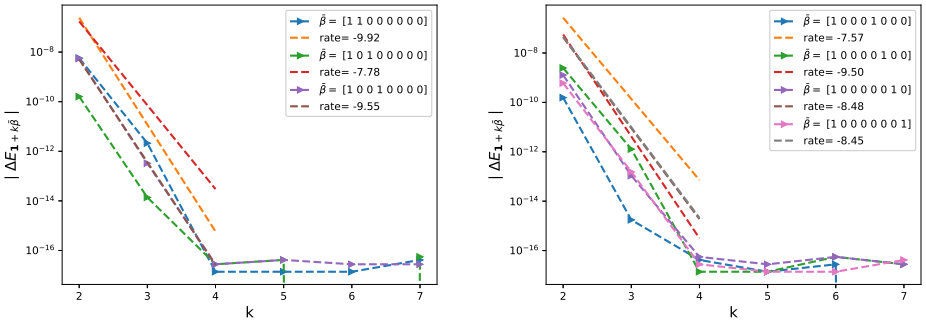
Remark 4.1. The choice of the hierarchy of quadrature points, $m(\boldsymbol{\beta})$, is flexible in the ASGQ algorithm and can be fixed by the user, depending on the convergence properties of the problem at hand. For instance, for the sake of reproducibility, in our numerical experiments we used a linear hierarchy: $m(\beta) = 4(\beta - 1) + 1,\ 1 \leq \beta$, for results of parameter set 1 in Table 5.1. For the remaining parameter sets in Table 5.1, we used a geometric hierarchy: $m(\beta) = 2^{\beta-1} + 1,\ 1 \leq \beta$.

Remark 4.2. As emphasized in [22], one important requirement to achieve the optimal performance of the ASGQ is to check the error convergence, defined by (4.6), of first and mixed difference operators. We checked this requirement in all our numerical experiments, and for illustration we show in Figures 4.2 and 4.3 the error convergence of first and second order differences for the case of parameter set 2 in Table 5.1. These plots show that: i) $\Delta \mathrm{E}_{\boldsymbol{\beta}}$ decreases exponentially fast with respect to β_i, and ii) $\Delta \mathrm{E}_{\boldsymbol{\beta}}$ has a product structure since we observe a faster error decay for second differences compared to corresponding first difference operators.



(a) (b)

Figure 4.2: The rate of error convergence of first order differences $|\Delta \mathrm{E}_{\boldsymbol{\beta}}|$, defined by (4.6), ($\boldsymbol{\beta} = \mathbf{1} + k\overline{\boldsymbol{\beta}}$) with respect to $\mathbf{W}^{(1)}$ (a) and with respect to $\mathbf{W}^{(2)}$ (b), for parameter set 2 in Table 5.1. The number of quadrature points used in the i-th dimension is $N_i = 2^{\beta_i - 1} + 1$.



(a) (b)

Figure 4.3: The rate of error convergence of second order differences $|\Delta \mathrm{E}_{\boldsymbol{\beta}}|$, defined by (4.6), ($\boldsymbol{\beta} = \mathbf{1} + k\overline{\boldsymbol{\beta}}$) with respect to $\mathbf{W}^{(1)}$ (a) and with respect to $\mathbf{W}^{(2)}$ (b), for parameter set 2 in Table 5.1. The number of quadrature points used in the i-th dimension is $N_i = 2^{\beta_i - 1} + 1$.

Remark 4.3. The analiticity assumption, stated in the beginning of Section 4.1, is crucial for the optimal performance of our proposed method. In fact, although we face the issue of the “curse of dimensionality"when increasing N, the analiticity of f implies a spectral convergence for sparse grids quadrature.

4.2 Quasi Monte Carlo (QMC)

A second type of deterministic quadrature that we test in this work is the randomized QMC method. Specifically, we use the lattice rules family of QMC [35, 15, 32]. The main input for the lattice rule is one integer vector with d component (d dimension of the integration problem).

In fact, given an integer vector $z = (z_1, \ldots, z_d)$ known as *the generating vector*, a (rank-1) lattice rule with n points takes the form

$$Q_n(f) := \frac{1}{n} \sum_{k=0}^{n-1} f\left(\frac{kz \bmod n}{n} \right). \tag{4.8}$$

The quality of the lattice rule depends on the choice of the generating vector. Due to the modulo operation, it suffices to consider the values from 1 up to $n-1$. Furthermore, we restrict the values to those relatively prime to n, to ensure that every one-dimensional projection of the n points yields n distinct values. Thus, we write $\mathbf{z} \in \mathbb{U}_n^d$, with $\mathbb{U}_n := \{z \in \mathbb{Z} : 1 \leq z \leq n-1 \text{ and } \gcd(z, n) = 1\}$. For practical purposes, we choose n to be a power of 2. The total number of possible choices for the generating vector is then $(n/2)^d$.

To get an unbiased approximation of the integral, we use a randomly shifted lattice rule, which also allows us to obtain a practical error estimate in the same way as the MC method. It works as follows. We generate q independent random shifts $\Delta^{(i)}$ for $i = 0, \ldots, q-1$ from the uniform distribution of $[0,1]^d$. For the same fixed lattice generating vector z, we compute the q different shifted lattice rule approximations and denote them by $Q_n^{(i)}(f)$ for $i = 0, \ldots, q-1$.We then take the average

$$\overline{Q}_{n,q}(f) = \frac{1}{q} \sum_{i=0}^{q-1} Q_n^{(i)}(f) = \frac{1}{q} \sum_{i=0}^{q-1} \left(\frac{1}{n} \sum_{k=0}^{n-1} f\left(\frac{kz + \Delta^{(i)} \bmod n}{n} \right) \right) \tag{4.9}$$

as our final approximation to the integral and the total number of samples of the randomized QMC method is $M^{\text{QMC}} = q \times n$.

We note that since we are dealing with Gaussian randomness and with integrals in infinite support, we use the inverse of the standard normal cumulative distribution function as a pre-transformation to map the problem to $[0,1]$ and then use the randomized QMC. Furthermore, in our numerical test, we use a pre-made point generator using latticeseq_b2.py in python from `https://people.cs.kuleuven.be/~dirk.nuyens/qmc-generators/`.

4.3 Brownian bridge (Bb) construction

In the literature of ASGQ and QMC, several hierarchical path generation methods (PGMs) have been proposed to reduce the effective dimension. Among these techniques, we mention Bb construction [29, 30, 13], principal component analysis (PCA) [1] and linear transformation (LT) [23].

In our context, the Brownian motion on a time discretization can be constructed either sequentially using a standard random walk construction, or hierarchically using other PGMs, as listed above. For our purposes, to make an effective use of ASGQ or QMC methods, which benefit from anisotropy, we use the Bb construction since it produces dimensions with different importance, contrary to a random walk procedure for which all the dimensions of the stochastic space have equal importance. In fact, Bb uses the first several coordinates of the low-discrepancy points to determine the general shape of the

Brownian path, and the last few coordinates influence only the fine detail of the path. Consequently, this representation reduces the effective dimension of the problem, which results in accelerating the ASGQ and QMC methods by reducing the computational cost.

Let us denote $\{t_i\}_{i=0}^N$ as the grid of time steps. Then the Bb construction [21] 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

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

where $\rho = \frac{j-i}{k-i}$.

4.4 Richardson extrapolation

Another representation that we couple with the ASGQ and QMC methods is Richardson extrapolation [36]. In fact, applying level K_{R} (level of extrapolation) of Richardson extrapolation dramatically reduces the bias, and as a consequence reduces the number of time steps N needed in the coarsest level to achieve a certain error tolerance. As a consequence, Richardson extrapolation directly reduces the total dimension of the integration problem for achieving some error tolerance.

Let us denote by $(X_t)_{0\le t\le T}$ a certain stochastic process and by $(\widehat{X}^h_{t_i})_{0\le t_i\le T}$ its approximation using a suitable scheme with a time step h. Then, for sufficiently small h, and a suitable smooth function f, we assume that

$$\mathrm{E}\left[f(\widehat{X}^h_T)\right] = \mathrm{E}\left[f(X_T)\right] + ch + \mathcal{O}\left(h^2\right). \tag{4.10}$$

Applying (4.10) with discretization step $2h$, we obtain

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

implying

$$2\mathrm{E}\left[f(\widehat{X}^{2h}_T)\right] - \mathrm{E}\left[f(\widehat{X}^h_T)\right] = \mathrm{E}\left[f(X_T)\right] + \mathcal{O}\left(h^2\right).$$

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

$$I(J,K_{\mathsf{R}}) = \frac{2^{K_{\mathsf{R}}} I(J,K_{\mathsf{R}}-1) - I(J-1,K_{\mathsf{R}}-1)}{2^{K_{\mathsf{R}}}-1}, \quad J = 1,2,\ldots, K_{\mathsf{R}} = 1,2,\ldots$$

Remark 4.4. We emphasize that throughout our work, we are interested in the pre-asymptotic regime (a small number of time steps), and the use of Richardson extrapolation is justified by conjecture 3.1 and our observed experimental results in that regime (see Section 5.1), which suggest a convergence of order one for the weak error.

5 Numerical experiments

In this section, we show the results obtained through the different numerical experiments, conducted across different parameter constellations for the rBergomi model. Details about these examples are

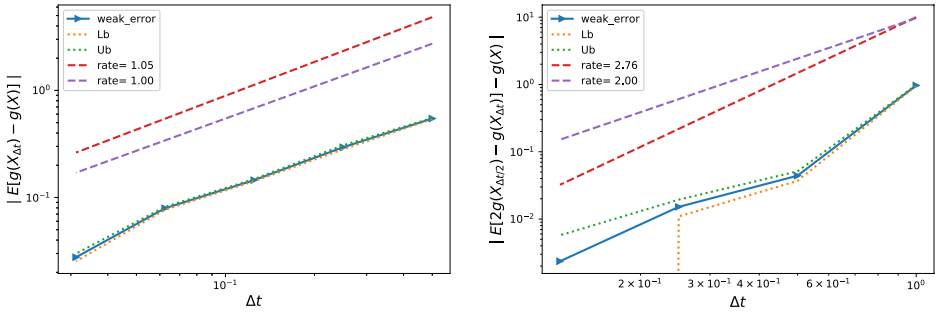
presented in Table 5.1. The first set is the one that is closest to the empirical findings [8, 20], which suggest that $H \approx 0.1$. The choice of parameter values of $\nu = 1.9$ and $\rho = -0.9$ is justified by [4], where it is shown that these values are remarkably consistent with the SPX market on 4th February 2010. For the remaining three sets in Table 5.1, we wanted to test the potential of our method for a very rough case, that is $H = 0.02$, for three different scenarios of moneyness, S_0/K. In fact, hierarchical variance reduction methods, such as Multi-level Monte Carlo (MLMC), are inefficient in this context because of the poor behavior of the strong error, that is of the order of H [31]. We emphasize that we checked the robustness of our method for other parameter sets, but for illustrative purposes, we only show results for the parameters sets presented in Table 5.1. For all our numerical experiments, we consider a number of time steps $N \in \{2, 4, 8, 16\}$, and all reported errors are relative errors, normalized by the reference solutions provided in Table 5.1.

Parameters	Reference solution
Set 1: $H = 0.07, K = 1, S_0 = 1, T = 1, \rho = -0.9, \eta = 1.9, \xi_0 = 0.235^2$	0.0791 $(5.6e{-}05)$
Set 2: $H = 0.02, K = 1, S_0 = 1, T = 1, \rho = -0.7, \eta = 0.4, \xi_0 = 0.1$	0.1246 $(9.0e{-}05)$
Set 3: $H = 0.02, K = 0.8, S_0 = 1, T = 1, \rho = -0.7, \eta = 0.4, \xi_0 = 0.1$	0.2412 $(5.4e{-}05)$
Set 4: $H = 0.02, K = 1.2, S_0 = 1, T = 1, \rho = -0.7, \eta = 0.4, \xi_0 = 0.1$	0.0570 $(8.0e{-}05)$

Table 5.1: Reference solution, which is the approximation of the call option price under the rBergomi model, defined in (2.4), using MC with 500 time steps and number of samples, $M = 8 \times 10^6$, for different parameter constellations. The numbers between parentheses correspond to the statistical errors estimates.

5.1 Weak error

We start our numerical experiments by accurately estimating the weak error (bias), discussed in Section 3, for the different parameter sets in Table 5.1, with and without Richardson extrapolation. For illustrative purposes, we only show the weak errors related to set 1 in Table 5.1 (see Figure 5.1). We note that we observed similar behavior for the other parameter sets, with slightly worse rates for some cases. We emphasize that the reported weak rates correspond to the pre-asymptotic regime that we are interested in. We are not interested in estimating the rates specifically but rather obtaining a sufficiently precise estimate of the weak error (bias), $\mathcal{E}_B(N)$, for different numbers of time steps N. For a fixed discretization, the corresponding estimated biased solution will be set as a reference solution to the ASGQ method in order to estimate the quadrature error $\mathcal{E}_Q(\text{TOL}_{\text{ASGQ}}, N)$.



(a) (b)

Figure 5.1: The convergence of the weak error $\mathcal{E}_B(N)$, defined in (3.1), using MC, for set 1 parameter in Table 5.1. We refer to C_{RB} as $\mathrm{E}\left[g(X)\right]$, and to C^N_{RB} as $\mathrm{E}\left[g(X_{\Delta t})\right]$. The upper and lower bounds are 95% confidence intervals. a) without Richardson extrapolation. b) with Richardson extrapolation (level 1).

5.2 Comparing the errors and computational time for MC, QMC and ASGQ

In this section, we conduct a comparison between MC, QMC and ASGQ in terms of errors and computational time. We show tables and plots reporting the different relative errors involved in the MC and QMC methods (bias and statistical error estimates), and in ASGQ (bias and quadrature error estimates). While fixing a sufficiently small relative error tolerance in the price estimates, we compare the computational time needed for all methods to meet the desired error tolerance. We note that in all cases the actual work (runtime) is obtained using an Intel(R) Xeon(R) CPU E5-268 architecture.

Through our conducted numerical experiments for each parameter set, we follow these steps to achieve our reported results:

i) For a fixed number of time steps, N, we compute an accurate estimate, using a large number of samples, M, of the biased MC solution, C^N_{RB}. This step also provides us with an estimate of the bias error, $\mathcal{E}_B(N)$, defined by (4.2).

ii) The estimated biased solution, C^N_{RB}, is used as a reference solution to the ASGQ method to compute the quadrature error, $\mathcal{E}_Q(\text{TOL}_{\text{ASGQ}}, N)$, defined by (4.5).

iii) In order to compare the different methods, the number of samples, M^{QMC} and M^{MC}, are chosen so that the statistical errors of randomized QMC, $\mathcal{E}_{S,\text{QMC}}(M^{\text{QMC}})$, and MC, $\mathcal{E}_{S,\text{MC}}(M^{\text{MC}})$, satisfy

$$\mathcal{E}_{S,\text{QMC}}(M^{\text{QMC}}) = \mathcal{E}_{S,\text{MC}}(M^{\text{MC}}) = \mathcal{E}_B(N) = \frac{\mathcal{E}_{\text{tot}}}{2}, \tag{5.1}$$

where $\mathcal{E}_B(N)$ is the bias as defined in (4.2) and $\mathcal{E}_{\text{tot}}$ is the total error.

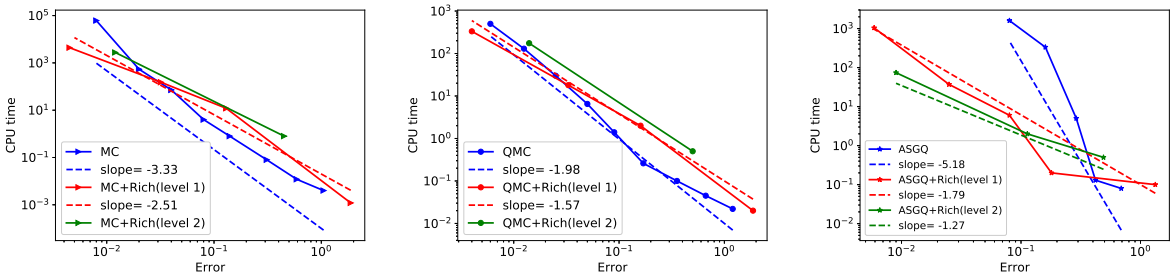
We show the summary of our numerical findings in Table 5.2, which highlights the computational gains achieved by ASGQ and QMC over the MC method to meet a certain error tolerance, which we set approximately to 1%. We note that the results are reported using the best configuration with Richardson extrapolation for each method. More detailed results for each case of parameter set, as in Table 5.1, are provided in Sections 5.2.1, 5.2.2, 5.2.3 and 5.2.4.

Parameter set	Total relative error	CPU time ratio (ASGQ/MC)	CPU time ratio (QMC/MC)
Set 1	1%	6.7%	10%
Set 2	0.2%	4.7%	1.4%
Set 3	0.4%	3.8%	4.7%
Set 4	2%	20%	10%

Table 5.2: Summary of relative errors and computational gains, achieved by the different methods. In this table, we highlight the computational gains achieved by ASGQ and QMC over the MC method to meet a certain error tolerance. We note that the ratios are computed for the best configuration with Richardson extrapolation for each method. We provide details about the way we compute these gains for each case in the following sections.

5.2.1 Case of parameters in Set 1 in Table 5.1

In this section, we conduct our numerical experiments for three different scenarios: i) without Richardson extrapolation, ii) with (level 1) Richardson extrapolation, and iii) with (level 2) Richardson extrapolation. Figure 5.2 shows a comparison of the numerical complexity for each method under the three different scenarios. From this Figure, we conclude that to achieve a relative error of 1%, level 1 of Richardson extrapolation is the optimal configuration for both the MC and the randomized QMC methods, and level 2 of Richardson extrapolation is the optimal configuration for the ASGQ method.



(a) (b) (c)

Figure 5.2: Comparing the numerical complexity of the different methods with the different configurations in terms of the level of Richardson extrapolation. a) MC methods. b) QMC methods. d) ASGQ methods.

We compare these optimal configurations for each method in Figure 5.3, and we show that both ASGQ and QMC outperform MC, in terms of numerical complexity. In particular, to achieve a total relative error of 1%, ASGQ coupled with level 2 of Richardson extrapolation requires approximately 6.7% of the work of MC coupled with level 1 of Richardson extrapolation, and QMC coupled with level 1 of Richardson extrapolation requires approximately 10% of the work of MC coupled with level 1 of Richardson extrapolation. We show more detailed outputs for the methods compared in Figure 5.3 in Appendix A.1.

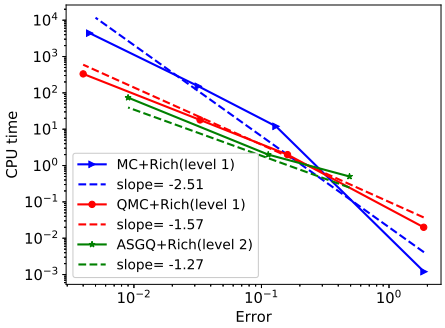


Figure 5.3: Computational work comparison for the different methods with the best configurations, as concluded from Figure 5.2, for the case of parameter set 1 in Table 5.1. This plot shows that to achieve a relative error below 1%, ASGQ coupled with level 2 of Richardson extrapolation and QMC coupled with level 1 of Richardson extrapolation have the same performance. Furthermore, they outperform significantly the MC method coupled with level 1 of Richardson extrapolation.

5.2.2 Case of parameters in Set 2 in Table 5.1

In this section, we only conduct our numerical experiments for the case without Richardson extrapolation, since the results show that we meet a small enough relative error tolerance without the need to apply Richardson extrapolation. We compare the different methods in Figure 5.4, and we determine that both ASGQ and QMC outperform MC, in terms of numerical complexity. In particular, to achieve a total relative error of about 0.2%, ASGQ requires approximately 4.7% of the work of MC, and QMC requires approximately 1.4% of the work of MC. We show more detailed outputs for the methods compared in Figure 5.4 in Appendix A.2.

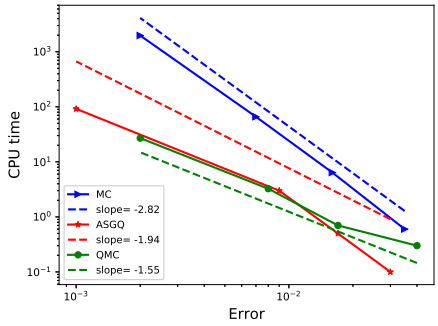


Figure 5.4: Computational work comparison for the different methods, for the case of parameter set 2 in Table 5.1. This plot shows that to achieve a relative error below 1%, ASGQ and QMC have similar performance and they outperform the MC method significantly in terms of computational time.

5.2.3 Case of parameters in Set 3 in Table 5.1

In this section, we only conduct our numerical experiments for the case without Richardson extrapolation, since the results show that we meet a small enough relative error tolerance without the need to apply Richardson extrapolation. We compare the different methods in Figure 5.5, and we determine that both ASGQ and QMC outperform MC, in terms of numerical complexity. In particular, to achieve a total relative error of about 0.4%, ASGQ requires approximately 3.8% of the work of MC, and QMC

requires approximately 4.7% of the work of MC. We show more detailed outputs for the methods compared in Figure 5.5 in Appendix A.3.

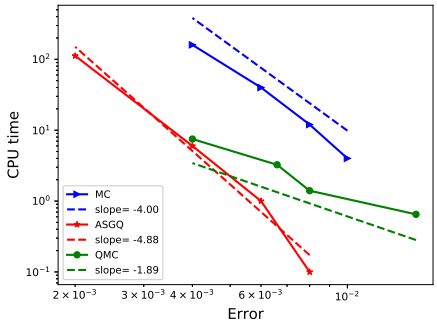


Figure 5.5: Comparison of computational work for the different methods, for the case of parameter set 3 in Table 5.1.

5.2.4 Case of parameters in Set 4 in Table 5.1

In this section, we only conduct our numerical experiments for the case without Richardson extrapolation. We compare the different methods in Figure 5.6, and we determine that both ASGQ and QMC outperform MC, in terms of numerical complexity. In particular, to achieve a total relative error of about 2%, ASGQ requires approximately 20% of the work of MC, and QMC requires approximately 10% of the work of MC. We show more detailed outputs for the methods compared in Figure 5.6 in Appendix A.4. Similar to the case of set 1 parameters, illustrated in section 5.2.1, we believe that Richardson extrapolation will improve the performance of the ASGQ and QMC methods. We should also point out that, since we are in the out of the money regime in this case, a fairer comparison of the methods may be done after coupling them with an importance sampling method, so that more points are sampled in the right region of the payoff function.

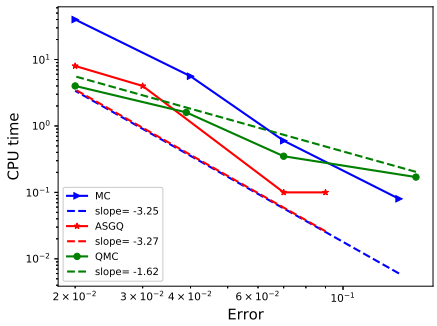


Figure 5.6: Comparison of computational work for the different methods, for the case of parameter set 4 in Table 5.1.

6 Conclusions and future work

In this work, we propose novel, fast option pricers, for options whose underlyings follow the rBergomi model as in [4]. The new methods are based on hierarchical deterministic quadrature methods: i)

ASGQ using the same construction as in [22], and ii) the QMC method. Both techniques are coupled with Brownian bridge construction and Richardson extrapolation.

Given that the only prevalent option, in this context, is to use different variants of the MC method, which is computationally expensive, our first contribution is that we uncover the available regularity in the rBergomi model and design novel approaches based on an ASGQ and QMC. These approaches open a new research direction in this field to investigate the performance of other methods besides MC, for pricing and calibrating under the rBergomi model. Our second contribution is that we reduce the computational cost through bias reduction by using Richardson extrapolation. Finally, assuming one targets price estimates with a sufficiently small relative error tolerance, our proposed method demonstrates substantial computational gains over the standard MC method, when pricing under the rBergomi model, even for very small values of the Hurst parameter. We show these gains through our numerical experiments for different parameter constellations. We clarify that we do not claim that these gains will hold in the asymptotic regime, i.e., for higher accuracy requirements. Furthermore, the use of Richardson extrapolation is justified in the pre-asymptotic regime, in which our observed experimental results suggest a convergence of order one for the weak error. We emphasize that, to the best of our knowledge, no proper weak error analysis has been done in the rough volatility context.

In this work, we limit ourselves to compare our novel proposed method against the standard MC. A more systematic comparison against the variant of MC proposed in [28] can be carried out but this remains for a future study. Another future research direction is to provide a reliable method for controlling the quadrature error for ASGQ which is, to the best of our knowledge, still an open research problem. This is even more challenging in our context, especially for low values of H. We emphasize that the main aim of this work is to illustrate the high potential of deterministic quadrature, when coupled with hierarchical representations, for pricing options under the rBergomi model. Finally, accelerating our novel methods can be achieved by using better versions of the ASGQ or QMC methods.

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A Appendix

A.1 Case of set 1 parameters in table 5.1

Method	Steps			
	$1-2$	$2-4$	$4-8$	$8-16$
QMC + level 1 of Richardson extrapolation	$\mathbf{1.87}$ (0.96,0.91)	$\mathbf{0.16}$ (0.07,0.09)	$\mathbf{0.033}$ (0.015,0.018)	$\mathbf{0.0044}$ (0.002,0.002)
M(# QMC samples)	128	8192	131072	2097152
MC + level 1 of Richardson extrapolation	$\mathbf{1.88}$ (0.96,0.92)	$\mathbf{0.14}$ (0.07,0.07)	$\mathbf{0.03}$ (0.015,0.015)	$\mathbf{0.0044}$ (0.002,0.0024)
M(# MC samples)	4×10	8×10^3	16×10^4	5×10^5

Table A.1: Total relative error of MC and randomized QMC coupled with Richardson extrapolation (level 1), to compute the call option price for different numbers of time steps. The values between parentheses correspond to the different errors contributing to the total relative error: the bias and the statistical errors. The number of MC and QMC samples, M, are chosen to satisfy (5.1).

Method	Steps			
	$1-2$	$2-4$	$4-8$	$8-16$
QMC + level 1 of Richardson extrapolation	0.018	2	18	333
MC + level 1 of Richardson extrapolation	0.0012	12	152	4400

Table A.2: Comparison of the computational time (in seconds) of MC and randomized QMC coupled with Richardson extrapolation (level 1) to compute the call option price of the rBergomi model for different numbers of time steps. The average MC CPU time is computed over 100 runs.

Method	Steps	
	$1-2-4$	$2-4-8$
ASGQ + level 2 of Richardson extrapolation ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	$\mathbf{0.54}$ (0.24,0.30)	$\mathbf{0.113}$ (0.006,0.107)
ASGQ + level 2 of Richardson extrapolation ($\text{TOL}_{\text{ASGQ}} = 5.10^{-2}$)	$\mathbf{0.49}$ (0.24,0.25)	$\mathbf{0.009}$ (0.006,0.003)

Table A.3: Total relative error of ASGQ, coupled with Richardson extrapolation (level 2), to compute the call option price for different numbers of time steps. The values between parentheses correspond to the different errors contributing to the total relative error: the bias and quadrature errors.

Method	Steps	
	$1-2-4$	$2-4-8$
ASGQ + level 2 of Richardson extrapolation ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	0.2	2
ASGQ + level 2 of Richardson extrapolation ($\text{TOL}_{\text{ASGQ}} = 5.10^{-2}$)	0.5	74

Table A.4: Comparison of the computational time (in seconds) of ASGQ coupled with Richardson extrapolation (level 2) to compute the call option price of the rBergomi model for different numbers of time steps.

A.2 Case of set 2 parameters in table 5.1

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	**0.03** (0.02,0.01)	**0.022** (0.008,0.014)	**0.022** (0.004,0.018)	**0.017** (0.001,0.016)
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	**0.03** (0.02,0.01)	**0.017** (0.008,0.009)	**0.008** (0.004,0.004)	**0.001** ($0.001, 4e{-}04$)
QMC	**0.04** (0.02,0.02)	**0.017** (0.008,0.009)	**0.008** (0.004,0.004)	**0.002** (0.001,0.001)
M(# QMC samples)	4096	8192	32768	262144
MC	**0.04** (0.02,0.02)	**0.016** (0.008,0.008)	**0.007** (0.004,0.003)	**0.002** (0.001,0.001)
M(# MC samples)	16×10^3	8×10^4	4×10^5	4×10^6

Table A.5: Total relative error of the different methods without Richardson extrapolation, to compute the call option price for different numbers of time steps. The values between parentheses correspond to the different errors contributing to the total relative error; for ASGQ we report the bias and quadrature errors and for MC and QMC we report the bias and the statistical errors estimates. The number of MC and QMC samples, M, are chosen to satisfy (5.1).

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	0.1	0.1	0.2	0.8
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	0.1	0.5	8	92
QMC method	0.3	0.7	3.25	27
MC method	0.6	6.4	66	1976

Table A.6: Comparison of the computational time (in seconds) of the different methods to compute the call option price of the rBergomi model for different numbers of time steps. The average MC CPU time is computed over 100 runs.

A.3 Case of set 3 parameters in table 5.1

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	**0.008** (0.006,0.002)	**0.009** (0.004,0.005)	**0.008** (0.003,0.005)	**0.009** (0.002,0.007)
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	**0.008** (0.006,0.002)	**0.009** (0.004,0.005)	**0.005** (0.003,0.002)	**0.002** (0.002,$1e{-}04$)
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-3}$)	**0.008** (0.006,0.002)	**0.006** (0.004,0.002)	**0.003** (0.003,$1e{-}04$)	**0.002** (0.002,$1e{-}04$)
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-4}$)	**0.006** (0.006,$4e{-}04$)	**0.004** (0.004,$2e{-}04$)	**0.003** (0.003,$1e{-}04$)	–
QMC	**0.015** (0.006,0.009)	**0.008** (0.004,0.004)	**0.0066** (0.003,0.0036)	**0.004** (0.002,0.002)
M(# QMC samples)	$2^3 \times 2^{10} = 8192$	$2^3 \times 2^{11} = 16384$	$2^3 \times 2^{12} = 32768$	$2^3 \times 2^{13} = 65536$
MC	**0.01** (0.006,0.005)	**0.008** (0.004,0.004)	**0.006** (0.003,0.003)	**0.004** (0.002,0.002)
M(# MC samples)	8×10^4	16×10^4	24×10^4	32×10^4

Table A.7: Total relative error of the different methods without Richardson extrapolation, to compute the call option price for different numbers of time steps. The values between parentheses correspond to the different errors contributing to the total relative error; for ASGQ we report the bias and quadrature errors and for MC and QMC we report the bias and the statistical errors estimates. The number of MC and QMC samples, M, are chosen to satisfy (5.1).

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	0.1	0.1	0.1	1
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	0.1	0.15	9	112
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-3}$)	0.2	2	27	2226
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-4}$)	1	6	136	–
QMC method	0.65	1.4	3.25	7.5
MC method	4	12	40	160

Table A.8: Comparison of the computational time (in seconds) of the different methods to compute the call option price of the rBergomi model for different numbers of time steps. The average MC CPU time is computed over 100 runs.

A.4 Case of set 4 parameters in table 5.1

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	$\mathbf{0.09}$ $(0.07,0.05)$	$\mathbf{0.07}$ $(0.03,0.04)$	$\mathbf{0.07}$ $(0.02,0.05)$	$\mathbf{0.06}$ $(0.01,2e{-}04)$
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	$\mathbf{0.09}$ $(0.07,5e{-}04)$	$\mathbf{0.07}$ $(0.03,0.04)$	$\mathbf{0.02}$ $(0.02,3e{-}04)$	$\mathbf{0.02}$ $(0.01,2e{-}04)$
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-3}$)	$\mathbf{0.07}$ $(0.07,5e{-}04)$	$\mathbf{0.03}$ $(0.03,4e{-}04)$	$\mathbf{0.02}$ $(0.02,3e{-}04)$	$\mathbf{0.01}$ $(0.01,2e{-}04)$
QMC	$\mathbf{0.155}$ $(0.07,0.085)$	$\mathbf{0.07}$ $(0.03,0.04)$	$\mathbf{0.039}$ $(0.02,0.019)$	$\mathbf{0.02}$ $(0.01,0.01)$
M(# QMC samples)	$2^3 \times 2^8 = 2048$	$2^3 \times 2^9 = 4096$	$2^3 \times 2^{11} = 16384$	$2^3 \times 2^{12} = 32768$
MC	$\mathbf{0.14}$ $(0.07,0.07)$	$\mathbf{0.07}$ $(0.03,0.04)$	$\mathbf{0.04}$ $(0.02,0.02)$	$\mathbf{0.02}$ $(0.01,0.01)$
M(# MC samples)	24×10^2	8×10^3	32×10^3	8×10^4

Table A.9: Total relative error of the different methods without Richardson extrapolation, to compute the call option price for different numbers of time steps. The values between parentheses correspond to the different errors contributing to the total relative error; for ASGQ we report the bias and quadrature errors and for MC and QMC we report the bias and the statistical errors estimates. The number of MC and QMC samples, M, are chosen to satisfy (5.1).

Method	Steps			
	2	4	8	16
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-1}$)	0.1	0.1	0.2	0.5
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-2}$)	0.1	0.1	8	97
ASGQ ($\text{TOL}_{\text{ASGQ}} = 10^{-3}$)	0.7	4	26	1984
QMC method	0.17	0.35	1.6	4
MC method	0.08	0.6	5.6	40

Table A.10: Comparison of the computational time (in seconds) of the different methods to compute the call option price of rBergomi model for different numbers of time steps. The average MC CPU time is computed over 100 runs.