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Electricity Derivatives

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Abstract: In this paper we propose an algorithm for pricing derivatives written on electricity in an incomplete market setting. A discrete time model for price dynamics which embodies the main features of electricity price revealed by simple time series analysis is considered. We use jointly Binomial and Monte Carlo methods for pricing under a risk-neutral measure of which we prove the existence.

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1 Introduction

Electricity markets are becoming a popular field of research amongst academics because of the lack of appropriate models for describing electricity price behavior and pricing derivatives instruments. Models for price dynamics must take into account seasonalities and spiky behavior of jumps which seem hard to model by standard jump processes. Without good models for electricity price dynamics it is difficult to think about good models for futures, forward, swap or option pricing. As a result, very often *pratictioners* are forced to employ models based on the cost-of-carry for their needs.

There are several reasons which discourage the use of cost-of-carry models (see H. Geman and O. Vasiceck, 2001 and H. Geman and A. Roncoroni, 2001). Basically the most important arguments against them are related to the physical and temporal constraints of electricity as a non-storable commodity. Non-storability implies that arbitrage arguments cannot be used in defining a pricing model when electricity is the underlying of a derivative contract. Secondly, electricity transportation is based on the availability of line connections which can be damaged by rare and extreme events. Probably this kind of risk should be included in a good pricing model.

In this paper we do not try to solve all of the above problems but we simply propose an algorithm for pricing derivative instruments in an incomplete market setting. Our main idea is to include those features of electricity price behavior revealed by simple time series analysis in a discrete time model for electricity price dynamics. We use jointly Binomial and Monte Carlo methods for pricing under a risk-neutral measure. The existence of such a measure is discussed in the appendix.

The paper is organized as follows. In the next section we show the intuitions which are on the basis of our model, in section III we describe in detail how to implement the pricing and in section IV we present some simulation results for American call options. The last section remarks our main findings and some still open issues.

2 A discrete time model

In the following, the electricity price at time point $t > 0$ is denoted by E_t and spikes are assumed to occur at random times and with random durations as percentual changes on the previous price level. A spike is defined as a positive random percentual change in the previous price level of electricity and it is denoted as S_t when it happens at time t. The function $D(S_\tau) : \mathbb{R}^+ \to \mathbb{N}^+$ returns the duration of the most recent spike occurred at time $\tau < t$. We also define $Q(S_\tau) : \mathbb{R}^+ \to \mathbb{N}^+$ as the time at which the spike will break down. The diffusion is X_t, its parameters are μ and σ and depends on $\varepsilon_t \sim N(0,1)$. Electricity prices are assumed to follow

$$\Delta E_t = \Delta f(X_t, t) + W_t S_t E_{t-1} - Z_t S_\tau E_{t-1}, \qquad E_0 = X_0 \tag{1}$$

where

$$\Delta X_t = \mu X_t \Delta t + \sigma X_t \sqrt{\Delta t} \varepsilon_t$$

$$W_t = \begin{cases} 1 \text{ with probability } q_t \\ 0 \text{ with probability } 1 - q_t \end{cases}$$

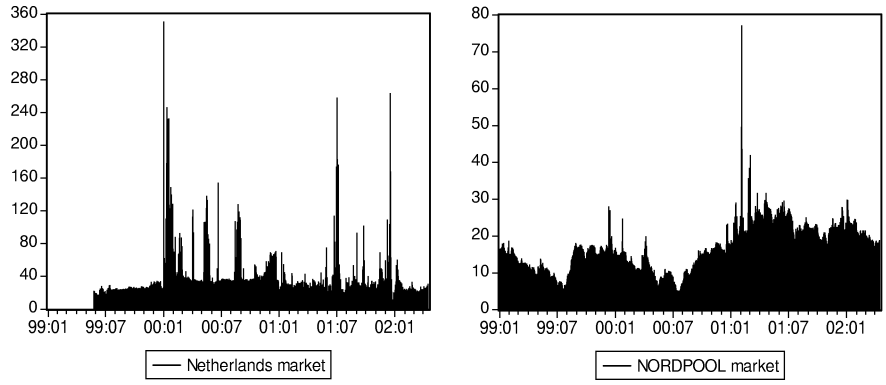

Figure 1: Electricity spot prices from Netherlands and NordPool markets.

$$Z_t = \begin{cases} 1 \text{ if } t = Q(S_\tau) \\ 0 \text{ otherwise} \end{cases}$$

The function $f(X_t, t)$ may allow for seasonalities in the diffusion, otherwise we may choose $f(X_t, t) = X_t$. The probability q_t is the probability that a spike is realized at time t, provided $t > Q(S_\tau)$. The duration of spike occurred at time $t^{(i)}$, $D(S_{t^{(i)}})$, is assumed to be independent of spike magnitude and price level.

Equation (1) defines changes in electricity prices in an additive way. The first component represents a diffusion, the second allows for positive percentual changes when a new spike happens and the third one models the collapsing of electricity prices when a spike breaks down. The last two components affect prices only when the indicator functions W_t or Z_t are equal to 1. The former depends on the probability that a spike happens, which we assume to be zero if the previous spike is still affecting prices, the latter is equal to one only at the time the previous spike breaks down.

For modeling purposes it is useful to define $p_t = \lambda(t)\Delta t$ as the unconditional probability of spike arrivals in Δt and to carry out the simulations using this measure. Indeed, we may simply simulate spikes in $t > Q(S_\tau)$ using p_t. Another advantage of using p_t to simulate spike arrivals is that it is easier to include seasonal dependence and dependence from previous spike realizations in the spike frequency parameter.

For example, m multiple peridiodicities may be included defining the spike frequency parameter like $\lambda(t) = \sum_{i=1}^{m} \omega_i \sin\left(2\pi\gamma_i t^i\right)$, where time t is expressed as a fraction of the year and ω_i and γ_i are parameters specified to match periodicities. Alternatively, dependence on the previous n realizations of the pure spike process can be introduced defining $\lambda(t) = \overline{\lambda} + \sum_{k=1}^{n} \theta^t \lambda(t-k)\mathbb{I}(t-k)$, where $0 < \theta < 1$ and $\mathbb{I}(j-k)$ is an indicator function which takes value 1 if a spike has happened at time $t-k$, and zero otherwise.

Another possible extension of our formulation regards the way the electricity price reverts to the diffusion process. If we call $t^{(i)}$ the time of the i-th spike, it

would be not difficult to model the decline of the electricity price over the period $D(S_{t^{(i)}})$ on a smoothed fashion rather than considering an istantaneous adjustment toward the diffusion process after $Q(S_{t^{(i)}})$. Anyway, in the remaining of this paper we consider the simplest case, with $p_t = \lambda \Delta t$.

3 Derivative Pricing

In this section we show how it is possible to implement an algorithm that is consistent with the model described in the previous section. The pricing of contracts such as Forwards or Swaps is not very complicate given that we can express the price in T of the former under a risk-adjusted measure as

$$F_T = \mathbb{E}\left[E_{(N-1)\Delta t} + \Delta f(X_{N\Delta t}, N\Delta t) + W_{N\Delta t} S_{N\Delta t} E_{(N-1)\Delta t} - Z_{N\Delta t} S_\tau E_{(N-1)\Delta t}\right]$$

where $T = N\Delta t$. The price of the latter in 0 is

$$SW_0 = \sum_{i=1}^{M} (F_{T_i} - L) e^{-r_i T_i}$$

where r_i is the discount rate for maturity T_i and L is the fixed price observed at the inception of the swap. The current fixed price for maturity M is determined solving $SW_0 = 0$.

The pricing of options is not immediate and in the remaining of this section we will show how to implement our model for them. We define options as rights to either buy or sell a given quantity of energy at the current spot price.

On the basis of the previous considerations and for the sake of clearness we list below the specific assumptions used during the implementation.

- *The distribution of the spike sizes follows a lognormal distribution.* We assume that the spiky behavior in electricity prices is governed by a random positive percentage variation in the level of the diffusion process with mode S_M and variance 0.04.

- *Spikes happen at random times but they cannot cumulate.* We generate spikes as realizations of a random processes driven by p_t's but we put some constraints to get a simulation under q_t's. For example, considering a binomial tree with period Δt, number of levels $N = T/\Delta t$, we may use the condition that draws from the uniform distribution over the interval $(0, 1)$ be smaller than $\lambda \Delta t$ to simulate N realizations of the variable $\mathbb{I}_t$, taking value 1 if a spike happens and zero otherwise. Here λ serves as spike frequency, that is the expected number of spikes in a year under p_t's. In practice, simulation under q_t's is possible imposing that a non-zero realization of $\mathbb{I}_t$ be considered as a realization of a spike only if it happens after the previous spike is broken down.

- *Spike duration is independent of spike frequency.* We use an exponential random variable with parameter θ to draw spike durations, $D(S_t)$. We set time in terms of years, i.e. $\theta = 0.01$ implies an expected duration of the spike is about 3 days.

The pricing is based on a three-step procedure. Let $\Delta t = T/N$, where N is the number of intervals in which we discretize the time to maturity T:

				$S_M = 0.1$		$S_M = 0.5$	
				$K = 120$	$K = 100$	$K = 120$	$K = 100$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	01.1375	07.0594	1.9645	07.3608
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	04.3546	11.2197	04.7711	11.4557
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	01.3416	07.3741	02.3670	08.1194
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	04.5267	11.6207	05.4795	12.8859
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	01.2208	07.4976	02.0696	08.8299
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	04.6356	11.5720	05.4623	12.6670
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	01.6977	08.1432	04.9431	11.9138
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	04.9571	12.0864	07.9667	15.0492
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	03.3493	10.5975	03.7466	11.2411
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	09.0318	16.2801	09.6239	17.0490
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	03.6694	11.1631	05.2833	13.1754
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	09.3584	16.7175	10.6889	17.9083
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	03.6148	11.0441	05.0901	12.4233
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	09.2296	16.5490	10.6972	17.9176
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	04.0952	11.6818	07.8177	14.4743
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	09.6601	17.4878	12.6447	20.9894

Table 1: European call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ. The mode of the distribution of spike intensities is S_M and $N = 100$.

1. In the first step we build a tree based on the diffusion process with parameter μ and σ;
2. In the second we simulate 1,000 pathways. Each pathway includes N spike realizations along the tree according to

$$I_t = \begin{cases} 1 \text{ if } u_t < \lambda \times \Delta t \\ 0 \text{ otherwise} \end{cases}$$

   where $u_t \sim U(0,1)$. For each time interval in which a spike arrives we draw the percentage change in X_t, S_t, from a lognormal distribution with mode S_M and variance 0.04. At the same time the duration of each spike occurrence is drawn from an exponential distribution with parameter θ. The process with spikes is obtained multiplying the nodes of the tree from $t^{(i)}$ to $T(S_{t^{(i)}})$ by $1+S_{t^{(i)}}$ for the *i-th* spike, being careful to avoid multiple spikes in the same periods. An example is shown in figure (2).
3. The last step requires the computation of the option price along each of the 1,000 trees. We then take their mean as a way to integrate over the different spike process realizations.

European options prices are influenced by the spike effect only if a spike arrives or is not yet broken down in the last period. The prices on each tree can be computed by the binomial method as the discounted option payoffs weighted for the risk neutral probabilities, given the strike price K. The average price across trees is the option price.

The price of an American option cannot be determined exactly but we can define the upper and lower bounds for the fair price. The lower bound is computed using an approximate condition for early option exercise. In fact it can

			$K = 80$	$K = 100$	$K = 120$
$T = 1.0$	$\sigma = 0.20$	$N = 100$	20.6834	7.6466	2.0647
$T = 1.0$	$\sigma = 0.20$	$N = 500$	20.6797	7.6594	2.0546
$T = 1.0$	$\sigma = 0.35$	$N = 100$	24.1465	13.3365	7.0071
$T = 1.0$	$\sigma = 0.35$	$N = 500$	24.1413	13.3588	6.9810
$T = 0.5$	$\sigma = 0.20$	$N = 100$	20.1149	5.5126	0.7068
$T = 0.5$	$\sigma = 0.20$	$N = 500$	20.1168	5.5224	0.7046
$T = 0.5$	$\sigma = 0.35$	$N = 100$	21.8756	9.6306	3.5556
$T = 0.5$	$\sigma = 0.35$	$N = 500$	21.8630	9.6478	3.5445

Table 2: American call option prices obtained by standard binomial pricing for some values of T, σ, N and K. The starting value of the underlying price is 100 and it is assumed to follow a simple diffusion.

be shown that if

$$E_t e^{-\sigma\sqrt{\Delta t}(N\Delta t - t)} - K > 0 \tag{2}$$

then it is rational to exercise the American call option in t, provided that no other spike happens later. The upper bound can be found going backward along each tree and averaging over the option prices obtained for each realization of the spike process.

4 Simulation results

Following the model just described we compute American call option price bounds assuming that the price of Electricity is 100\$ at time 0 and the risk free rate is 5%. In Table (2) we report American option prices under the usual Black-Scholes diffusion model for comparison. In Tables (4) - (15) we have computed derivative prices considering different values for the time to maturity (1 year and 6 months), strike (80, 100, 120), volatility (20% and 35%), spike magnitude (lognormal mode equal to 10% and 50%), frequency (1 and 3 expected number of spikes each year) and duration (0.01 and 0.03 *years*). The last two columns of the tables shows the call price computed using the sufficient condition, $\underline{C}_0$, and the backward recursion on the binomial tree, $\overline{C}_0$.

The number of periods in which we have divided the time to maturity is not really important for pricing. In practice what really matter about the choice of time steps is to avoid that several spikes with duration lower then Δt be excluded while valuation is carried out. In a more general setting, we may set Δt for each replication only after having determined the shortest duration of spikes for a given replication.

At first look, prices obtained under our model are much higher then those reported in Table (2). The difference is due to the inclusion of the spike process and the differences are particularly sensible to the degree of moneyness, time to maturity, λ and S_M. The diffusion coefficient σ has little importance because the risk it represents is overwhelmed by those implied by the spiky behavior of the electricity prices.

Considering the prices obtained including the condition in Equation (2) it appears that these are close to $\overline{C}_0$ when we refer to in-the-money options and the spread increases as long as moneyness decreases, reaching the highest level

		$t-Statistic$	$P-values$
$\hat{\beta}_1$	0.016370	0.004893	0.00111
$\hat{\beta}_2$	0.023631	0.000529	$2.96E-45$
$\hat{\beta}_3$	-0.018936	0.003423	$5.65E-13$
R^2	95%		
$F-statistic$	1022.514		0.000000
AIC	-5.780151		

Table 3: Estimation result from model (3).

when we are pricing out-of-the-money options, spikes are big and relatively frequent ($\lambda = 3$). In these cases $\underline{C}_0$ is however significantly greater than the corresponding European value in Table (2) because of the possibility of spikes occurring before the last period. That is different from the classical result in financial markets, that out-of-the money American options have values close to corresponding European options.

In the tables reporting pricing results there is evidence that the strategy implied in Equation (2) sometimes leads to a significant loss of value on early exercise. Therefore Equation (2) is not always adequate for pricing options and we need to correct the price in these cases. The spread is small when T, λ and S_M are small. In order to find a relation between $\overline{C}_0 - \underline{C}_0$ and the price process determinants, we express the spread standardized by the strike price as a function of the spike intensity, the product of the frequency parameter and time to maturity and the moneyness degree. The simple linear model

$$\left(\frac{\overline{C}_0 - \underline{C}_0}{K}\right)_i = \beta_1 S_{M,i} + \beta_2 T_i \lambda_i + \beta_3 \left(\frac{E_0}{K}\right)_i + u_i \tag{3}$$

is estimated for pricing settings with $S_M \geq 0.5$ and $N = 100$. Results in Table (3) show that this simple specification explains well the difference between the bounds and it has the feature to be quite general to avoid overfitting. The relation between upper and lower boundary is explained by Equation (4).

$$\overline{C}_0 = \underline{C}_0 + K\left(\hat{\beta}_1 S_M + \hat{\beta}_2 T\lambda + \hat{\beta}_3 \frac{E_0}{K}\right) \tag{4}$$

The largest spreads occur when spikes are very frequent ($\lambda = 5$). The complete simulation approach should be used in these cases having a new simulation begin from each node where early exercise is potentially convenient. Detailed results are shown in Tables (4) - (15).

5 Concluding Remarks

We present a model for the dynamics of electricity spot prices and we describe some applications of the model for pricing derivative instruments. The application proposed in detail is the pricing of American call options, assuming a

constant spike frequency, lognormally distributed spike magnitude and exponentially distributed spike durations. For this kind of derivative an exact fair price cannot be determined simply. It possible to find the upper and lower bound of the fair price under a risk-adjusted measure. The model can be generalized considering time dependent parameters and include seasonalities and even multiple periodicities as we have exemplified for λ.

Simulations results have shown that prices obtained under our algorithm are very different from those obtained by standard option pricing models. The lower bound is very easy to compute. The upper bound requires a greater effort. Often the two bounds are fairly close, suggesting that the lower bound is a close approximation of the fair price under most circumstances. However the bounds differ for out-of-the money options with high spike frequencies.

It is clear from the results that the most relevant determinants of the option price level are the parameters of the spike process. It would be useful to enrich the model in this direction, adding seasonalities and stylized facts to this component. Moreover, our pricing models have been computed under the risk-neutral measure. The existence of this measure is discussed in the appendix but the relationship between the physical and the risk-neutral measures is an important topic for future research. We believe that spike risk is largely idiosyncratic and this justifies the binomial pricing method as advocated by Merton (Merton R., 1992), but only long series of market data may cast light on this issue.

6 Appendix

Let F be the forward price for delivery at T, where T is any relevant time. Define F^* as the forward price of a contract that delivers electricity if no spike is in progress at T. If a spike is in progress F^* delivers against an additional payment equal to the spike intensity[1]. Let M be the expected intensity of the spike at T. Define

$$\pi = \frac{(F - F^*)}{M}$$

then a risk-neutral measure exists if and only if $0 < \pi < 1$.

PROOF: From the definition of π.

$$F = \pi M + (1 - \pi)0 + \int X d\widetilde{P}$$

where X is the spot price at time T and $\widetilde{P}$ is the forward risk neutral measure for the diffusion process without spikes. A similar proof holds for the risk neutral measure defined by futures contracts.

7 Bibliography

References

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ITM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	29.8750	29.9848
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.5986	29.7658
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	30.5422	30.7317
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	30.1514	30.3610
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	37.6916	38.3850
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	36.9241	38.0500
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	37.8888	38.9504
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	37.7231	38.9613
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	29.5485	29.6705
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.9932	30.1945
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	30.5383	30.6589
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	30.2876	30.5165
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	37.7446	38.3995
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	37.1316	38.1575
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	37.8791	38.8375
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	37.0842	38.2996

Table 4: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 80.

ITM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	36.1214	36.7029
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	36.2104	36.8911
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	37.2837	38.1680
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	37.2801	38.2733
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	42.3448	44.6130
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	41.4840	44.7876
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	42.1189	45.3512
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	41.3902	45.5511
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	36.0188	36.5551
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	35.3979	36.1548
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	36.8613	37.7634
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	37.2322	38.2289
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	42.1325	44.5772
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	41.3921	44.4825
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	42.0098	45.2732
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	41.0580	45.2355

Table 5: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 80.

ITM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	46.3913	46.4801
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	46.5027	46.9213
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	46.8861	47.2384
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	47.3166	47.9577
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	71.5896	72.7866
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	71.0383	73.5544
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	71.3235	73.7031
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	70.5442	73.9954
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	45.7253	45.9190
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	46.6874	47.0690
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	47.2720	47.5610
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	46.6034	47.2365
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	73.7413	74.6968
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	71.0943	73.3377
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	71.5541	73.1945
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	70.1634	73.0487

Table 6: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 80.

ITM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	62.5343	63.5429
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	62.1316	63.5358
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	62.2228	63.8457
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	63.7876	65.6090
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	84.9457	88.7413
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	82.4418	89.0597
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	83.5325	89.2921
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	81.9741	89.6744
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	64.3828	65.4066
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	61.3676	63.4218
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	62.4802	63.8345
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	63.2104	65.3867
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	85.6443	89.3603
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	83.3663	89.9129
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	82.9634	88.9521
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	80.6769	89.0712

Table 7: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 80.

ATM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	12.9826	13.2223
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	13.0809	13.2710
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	15.9707	16.2493
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	15.5470	15.9175
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	18.6140	19.9391
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	18.3560	19.7200
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	20.1706	21.9318
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	19.8078	21.4986
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	12.7450	12.9948
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	13.0198	13.2713
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	15.5891	15.9733
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	15.9066	16.3703
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	18.5443	19.7896
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	18.1380	19.4866
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	19.9624	21.7101
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	20.0721	21.9510

Table 8: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 100.

ATM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	18.5186	19.3222
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	18.5474	19.4738
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	22.0031	23.5042
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	21.6968	23.3463
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	21.8986	25.8139
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	21.6284	25.9550
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	23.4219	28.8784
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	23.4479	29.0103
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	18.6384	19.4981
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	18.6182	19.7847
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	21.9422	23.4627
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	21.4499	23.0300
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	22.2485	26.2281
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	21.8104	25.7352
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	23.7080	29.1479
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	23.0125	28.8168

Table 9: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 100.

ATM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	29.2419	29.4422
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.3349	29.8570
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	31.2238	31.7673
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	31.7474	32.4010
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	52.0969	54.0428
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	51.5843	54.7923
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	52.5536	55.5433
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	52.0156	55.8333
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	28.6794	28.9403
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.5670	29.9929
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	31.5247	32.0603
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	31.1372	31.8324
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	54.1376	55.8021
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	51.8601	54.5755
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	52.8258	55.0459
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	51.5920	54.9025

Table 10: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 100.

ATM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	44.6127	46.0056
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	44.3551	46.0665
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	45.8577	47.6927
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	47.0810	49.1886
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	64.4447	69.5363
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	62.1149	69.8241
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	63.4817	70.4774
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	62.4178	70.8811
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	46.3017	47.7776
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	43.6654	45.9829
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	45.9468	47.6148
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	46.6011	48.9510
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	64.3964	70.1050
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	62.9806	70.6535
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	62.7815	70.2011
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	61.0449	70.3456

Table 11: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 100.

OTM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	02.7645	03.1451
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	02.7800	03.1604
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	06.0904	06.6743
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	05.9745	06.6759
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	04.1711	05.9766
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	04.2016	06.0476
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	07.0232	09.7962
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	07.1634	09.8647
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	02.8829	03.2678
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	02.8327	03.2921
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	06.0658	06.8635
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	06.2296	06.9138
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	04.2663	06.1963
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	04.2507	06.2362
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	07.2157	09.9773
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	06.9814	09.8383

Table 12: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 120.

OTM	$S_M = 0.1$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	05.8406	07.3510
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	06.1324	07.5509
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	10.6793	13.0845
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	10.7492	13.0215
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	05.9835	11.3237
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	05.9308	11.0995
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	09.4740	17.2252
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	09.3099	17.0246
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	06.1037	07.6047
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	05.7246	07.4503
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	10.7727	13.1104
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	10.5357	13.3294
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	05.9233	11.3846
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	05.9878	11.3433
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	09.3918	17.3599
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	09.1443	17.2594

Table 13: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 120.

OTM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	17.6710	18.2194
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	18.1478	18.7939
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	19.7224	20.3172
$T = 0.5$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	19.9204	20.7207
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	34.6956	37.3718
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	34.2901	38.0985
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	35.2587	38.6438
$T = 0.5$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	35.0963	38.8652
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	17.8595	18.3396
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	17.9709	18.4808
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	19.8336	20.6625
$T = 0.5$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	19.6689	20.4965
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	35.1103	37.9307
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	34.9616	38.3003
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	35.0757	38.2893
$T = 0.5$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	35.1366	38.8880

Table 14: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 120.

OTM	$S_M = 0.5$				$\underline{C}_0$	$\overline{C}_0$
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	29.7326	31.5437
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.0364	31.1717
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	32.2088	34.4994
$T = 1.0$	$\theta = 0.01$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	32.1511	34.3449
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	44.4208	51.3083
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	42.3072	51.2874
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	43.8272	53.1472
$T = 1.0$	$\theta = 0.01$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	42.9827	52.8007
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 100$	30.5809	32.4505
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.20$	$N = 500$	29.4335	31.3746
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 100$	32.1465	34.1942
$T = 1.0$	$\theta = 0.03$	$\lambda = 1$	$\sigma = 0.35$	$N = 500$	32.4565	35.1242
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 100$	43.6222	51.7772
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.20$	$N = 500$	42.4879	51.3064
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 100$	43.2047	51.8437
$T = 1.0$	$\theta = 0.03$	$\lambda = 3$	$\sigma = 0.35$	$N = 500$	42.5801	52.9565

Table 15: American call option prices obtained by the algorithm using 1,000 realizations of a spike process for some values of T, θ, λ, σ, N. The mode of the distribution of spike intensities is S_M and the strike is 120.

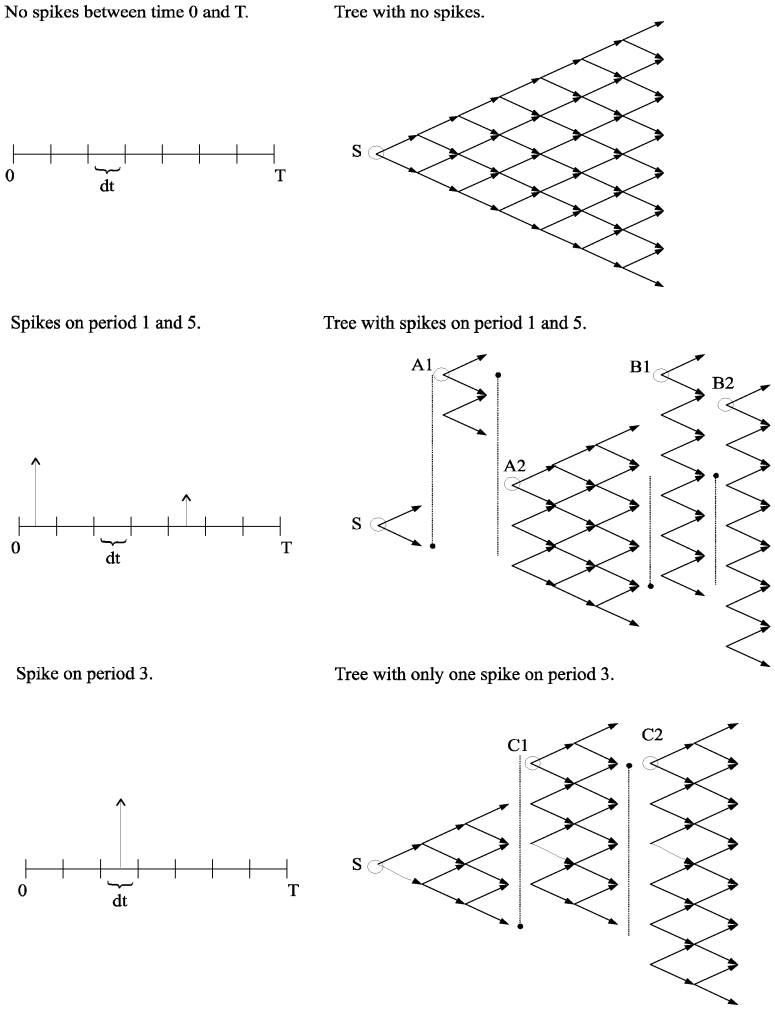

Figure 2: The figure show three examples of spike processes realizations over binomial trees. The number of levels affected by the spike is random, as well as the intensity of the spike magnitude.