

Price a Vanilla European Call Option

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Abstract

In this paper, we price a vanilla European call option under the Heston model and then simulate the monthly share price over a year using the Constant Elasticity of Variance (CEV) model, with the assumption of constant volatility each month. Monte Carlo simulations with varying sample sizes are run and the results are plotted against the closed form value for comparison.

1 Introduction

In this paper we go beyond the constant volatility assumption in the Black-Scholes model. Most of code implemented in this submission is derived from Module 5 [7] of the course.

We initialize most variables as given by the question.

- Option maturity is one year
- The option is struck at-the-money
- The current share price is \$100
- The risk-free continuously compounded interest rate is 8%
- The volatility for the underlying share is 30%

2 Fourier pricing technique under Heston model dynamics

Black-Scholes option pricing models assumed volatility of the underlying assets to be constant or a predetermined function of time, we will now implement a model which features instantaneous variance of asset price using volatility that evolves stochastically in time. Although there are several models incorporating stochastic volatility including introduced by Hull and White [1], Stein and Stein [2] and Heston [3] [4], we will implement Heston's constant interest rate model.

With the assumption that the underlying share follows the Heston model dynamics, the additional parameters required are specified as follows:

- $\nu_0 = 0.06$
- $\kappa = 9$
- $\theta = 0.06$
- $\rho = -0.4$

The Characteristic function is implemented using a function presented by Albrecher et al [5]. The function is written as:

$$\phi_{S_T} = \exp(C(\tau; u) + D(\tau; u)v_t + iu \log(S_t))$$

Where,

$$C(\tau; u) = ri\tau u + \theta\kappa[\tau x_- - \frac{1}{a} \log(\frac{1 - ge^{d\tau}}{1 - g})],$$

$$D(\tau; u) = (\frac{1 - e^{d\tau}}{1 - ge^{d\tau}})x_-,$$

$$\tau = T - t,$$

$$g = \frac{x_-}{x_+},$$

$$x_{\pm} = \frac{b \pm d}{2a},$$

$$d = \sqrt{b^2 - 4ac},$$

$$c = -\frac{u^2 + ui}{2},$$

$$b = \kappa - \rho\sigma iu,$$

$$a = \frac{\sigma^2}{2}$$

`[]`: *#Characteristic function code*

```
a = sigma**2/2
```

```
def b(u):
```

```

    return kappa - rho*sigma*1j*u

def c(u):
    return -(u**2+1j*u)/2

def d(u):
    return np.sqrt(b(u)**2-4*a*c(u))

def xminus(u):
    return (b(u)-d(u))/(2*a)

def xplus(u):
    return (b(u)+d(u))/(2*a)

def g(u):
    return xminus(u)/xplus(u)

def C(u):
    val1 = T*xminus(u)-np.log((1-g(u)*np.exp(-T*d(u)))/(1-g(u)))/a
    return r*T*1j*u + theta*kappa*val1

def D(u):
    val1 = 1-np.exp(-T*d(u))
    val2 = 1-g(u)*np.exp(-T*d(u))
    return (val1/val2)*xminus(u)

def log_char(u):
    return np.exp(C(u) + D(u)*v0 + 1j*u*np.log(S0))

def adj_char(u):
    return log_char(u-1j)/log_char(-1j)

```

Now we vectorize the code, calculate an estimate for integrals and calculate the Fourier estimate of our call price.

```

[]: delta_t = t_max/N
    from_1_to_N = np.linspace(1,N,N)
    t_n = (from_1_to_N-1/2)*delta_t

    #Integral calculations
    first_integral = sum((((np.exp(-1j*t_n*k_log)*adj_char(t_n)).imag)/t_n)*delta_t)
    second_integral = sum((((np.exp(-1j*t_n*k_log)*log_char(t_n)).imag)/t_n)*delta_t)

    #Call value
    fourier_call_val = S0*(1/2 + first_integral/np.pi)-np.exp(-r*T)*K*(1/2 +
    ↪second_integral/np.pi)
    fourier_call_val

```

□: 13.734895692109077

To see the effectiveness of the pricing option under Heston dynamics we will also price the call option under Black-Scholes assumption.

```
□: # Code for analytical solution for vanilla European Call option
d_1_stock = (np.log(S0/K)+(r + sigma**2/2)*(T))/(sigma*np.sqrt(T))
d_2_stock = d_1_stock - sigma*np.sqrt(T)

analytic_callprice = S0*norm.cdf(d_1_stock)-K*np.exp(-r*(T))*norm.cdf(d_2_stock)
analytic_callprice
```

□: 15.711312547892973

3 Simulate a share price path using CEV Model

Cox [6] developed the constant elasticity of variance (CEV) option pricing model, it attempts to capture stochastic volatility and is given by:

$$dS_t = \mu S_t dt + \sigma S_t^\gamma dW_t$$

If $\gamma = 1$ this model return the same value as Black-Scholes model, however if the value of $\gamma < 1$ we experience an effect called leverage effect where the volatility increases as the price decreases over subsequent time periods.

Based on the assumption that $\sigma(t_i, t_{i+1}) = \sigma(S_{t_i})^{\gamma-1}$, where $\sigma = 0.3$ and $\gamma = 0.75$. We can simulate the next step in a share price path using the following formula:

$$S_{t_{i+1}} = S_{t_i} e^{(r - \frac{\sigma^2(t_i, t_{i+1})}{2})(t_{i+1} - t_i) + \sigma(t_i, t_{i+1}) \sqrt{t_{i+1} - t_i} Z}$$

where S_{t_i} is the share price at time t_i , $\sigma(t_i, t_{i+1})$ is the volatility for the period $[t_i, t_{i+1}]$, r is the risk-free interest rate, and $Z \sim N(0, 1)$

First, we define our helper functions. The `next_share_price` function is used to calculate the evolution of the share price at $t+1$, from the share price at t . We generate the random variable Z from within this function. The effective sigma is also written as a function of the share price at t .

Just for exploration purposes, we also added a `varying_vol` flag, to allow us to switch between a constant volatility and varying volatility. We use the initial stock price instead of the previous price when assuming a constant volatility.

The other function is the `generate_share_price_path` function. We first create an empty numpy array of shape `(sample_size x timesteps+1)`. Note the addition of one element to the timestep, as the first element is equal to the initial stock price. We then iterate through each path, and each timestep, applying the `next_share_price` function against the previous share price. We then convert the result into a pandas DataFrame and return the results.

```
[7]: def next_share_price(prev_price, r, dT, sigma_const, gamma, sample_size,
    ↪varying_vol = True):
    Z = stats.norm.rvs(size=sample_size)
    if varying_vol:
        sigma = sigma_const*(prev_price)**(gamma-1)
    else:
        sigma = sigma_const*(S0)**(gamma-1)

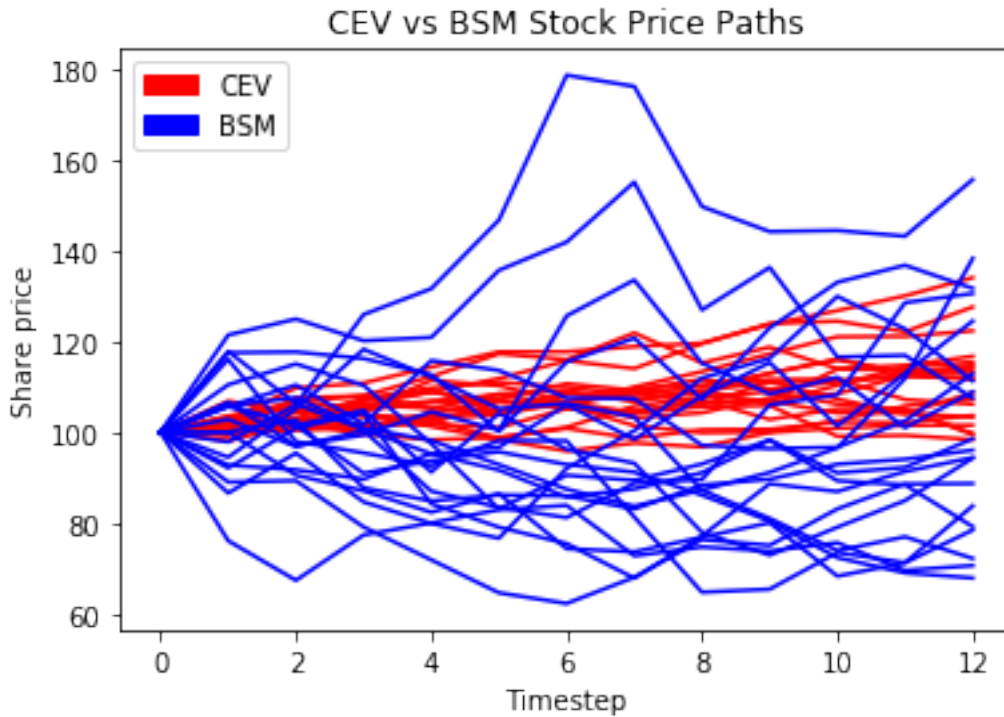
    return prev_price*np.exp((r-(sigma**2)/2)*(dT)+(sigma)*(np.sqrt(dT))*Z)

def generate_share_price_path(S0, r, T, sigma_const, gamma, sample_size,
    ↪timesteps, varying_vol = True):
    df = pd.DataFrame([S0]*sample_size)
    for t in range(1, timesteps+1):
        df[t] = next_share_price(df[t-1], r, 1/timesteps, sigma_const, gamma,
    ↪sample_size, varying_vol)
    return df.T

[8]: import matplotlib.patches as mpatches
T = 10
sample_size = 20

share_price_path_cev = generate_share_price_path(S0, r, T, sigma_const, gamma,
    ↪sample_size, timesteps)
share_price_path_black_scholes = generate_share_price_path(S0, r, T,
    ↪sigma_const, 1.0, sample_size, timesteps, varying_vol=False)

plt.plot(share_price_path_cev, color='red')
plt.plot(share_price_path_black_scholes, color='blue')
plt.xlabel("Timestep")
plt.ylabel("Share price")
red_patch = mpatches.Patch(color='red', label='CEV')
blue_patch = mpatches.Patch(color='blue', label='BSM')
plt.legend(handles=[red_patch, blue_patch], loc='upper left')
plt.title("CEV vs BSM Stock Price Paths")
plt.show()
```



Next, we create a python dictionary called `share_price_paths`, to hold our results for part 2. The key of this dictionary would be the number of sample price paths, while the values would be the dataframes containing the price paths. We also track the rough processing time required at each step, by printing the time when each iteration completes.

```
[9]: import time

T = 1
sample_sizes = range(1000, 50001, 1000)

share_price_paths = {}

print("Start generating share price path")
start = time.time()
for sample_size in sample_sizes:
    share_val = generate_share_price_path(S0, r, T, sigma_const, gamma,
    sample_size, timesteps, varying_vol=False)

    share_price_paths[sample_size] = share_val
    #print("Updated for sample size {} at {}".format(sample_size, datetime.
    datetime.now().strftime('%H:%M')))
end = time.time()
print(f"Generating all samples paths takes {(end - start):.2f}s")
```

Start generating share price path
Generating all samples paths takes 2.58s

To display our output, we show the first 10 price paths generated by our iteration with 1000 samples:

```
[10]: share_price_paths[1000].iloc[:, 0:10]
```

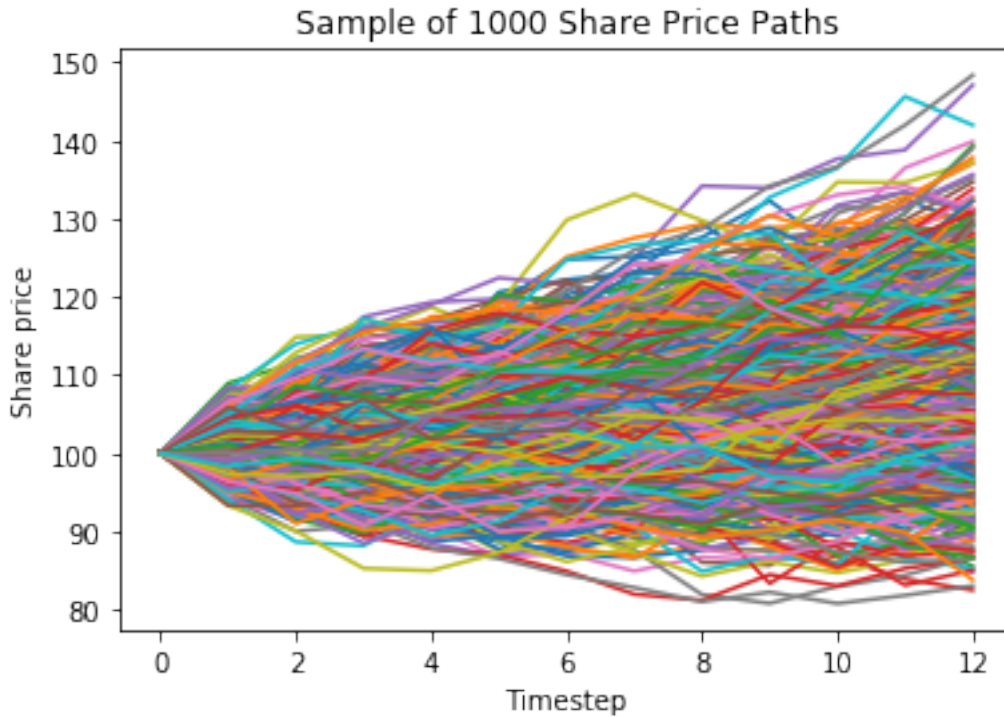
```
[10]:
```

	0	1	2	3	4	5 \
0	100.000000	100.000000	100.000000	100.000000	100.000000	100.000000
1	99.626771	99.374526	100.689569	97.065445	106.862386	99.918343
2	103.745565	96.967926	102.622183	96.451414	106.332275	96.640428
3	107.154631	96.585243	105.974778	93.207852	100.177288	99.129417
4	111.716818	95.838855	101.540594	94.146336	98.646601	102.592136
5	120.620494	93.477848	100.930914	94.502805	100.662067	103.175996
6	122.217586	87.674152	101.799340	91.076602	101.876289	102.336328
7	123.138256	87.108925	103.904210	94.061221	106.060742	103.426255
8	129.359695	87.871374	100.925245	92.948402	115.010833	98.206543
9	123.575048	87.571414	105.883449	95.799071	117.769685	97.640631
10	125.486476	88.836040	104.337774	96.829970	119.866089	100.623917
11	124.538067	92.114326	106.173600	98.493852	118.497793	99.093147
12	123.548415	92.619346	104.478810	98.081928	114.719969	94.669329

	6	7	8	9
0	100.000000	100.000000	100.000000	100.000000
1	106.483031	100.796117	100.030802	102.593647
2	105.512423	101.627748	98.448810	103.179244
3	107.821291	98.518154	97.598741	103.563761
4	108.394844	97.918995	99.489053	110.865271
5	108.425203	99.326116	97.269739	108.916593
6	107.844372	103.199284	98.432527	108.089622
7	108.269775	100.286497	101.084604	107.860547
8	108.268731	99.113198	101.552266	103.792957
9	103.400905	98.076554	100.633537	106.623775
10	107.548810	98.062335	97.583078	110.004438
11	104.394412	98.481303	94.325492	107.980799
12	103.306627	95.171645	94.012006	108.960908

Next, we plot the price paths for the iteration with 1000 samples,

```
[11]: plt.plot(share_price_paths[1000])
plt.xlabel('Timestep')
plt.ylabel('Share price')
plt.title('Sample of 1000 Share Price Paths')
plt.show()
```



4 Monte Carlo estimates

Using Monte Carlo, we calculate the price of the vanilla call option as follows:

```
[12]: price_estimate = []
      price_std = []

      for size in sample_sizes:
          S_Ts = share_price_paths[size].iloc[12, :]
          payoff = np.maximum(S_Ts - K, 0)
          discounted_price = np.exp(-r*T)*payoff
          price_estimate.append(discounted_price.mean())
          price_std.append(discounted_price.std()/np.sqrt(size))

[13]: print("The price estimated by Monte Carlo when using sample size of 50,000 is :_
      ↳{: .3f}".format(price_estimate[-1]))
```

The price estimated by Monte Carlo when using sample size of 50,000 is : 8.694

We then compare with calculation of CEV model using noncentralchi-squared


```
[14]: import numpy as np
import matplotlib.pyplot as plt
from scipy.stats import ncx2

S0 = 100
sigma = 0.3
gamma = 0.75
r = 0.08
T = 1
```

```
[15]: z = 2 + 1/(1-gamma)
def C(t,K):
    kappa = 2*r/(sigma**2*(1-gamma)*(np.exp(2*r*(1-gamma)*t)-1))
    x = kappa*S0**(2*(1-gamma))*np.exp(2*r*(1-gamma)*t)
    y = kappa*K**(2*(1-gamma))
    return S0*(1-ncx2.cdf(y,z,x))-K*np.exp(-r*t)*ncx2.cdf(x,z-2,y)
```

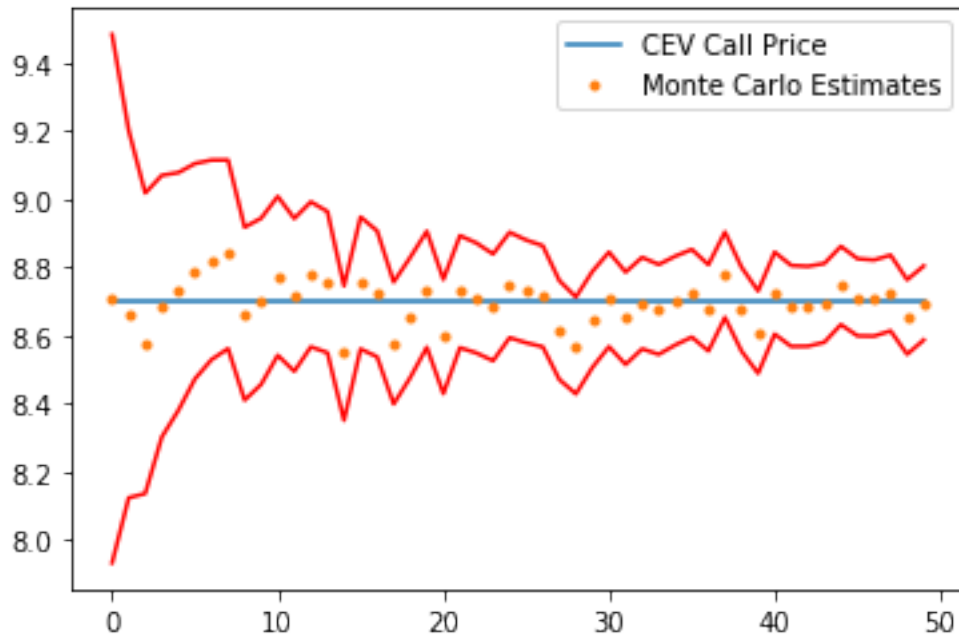
```
[16]: cev_call_price = C(T, 100)
```

```
[17]: print("The price calculated via CEV model using noncentral chi-squared_
→distribution is : {:.3f}".format(cev_call_price))
```

The price calculated via CEV model using noncentral chi-squared distribution is : 8.702

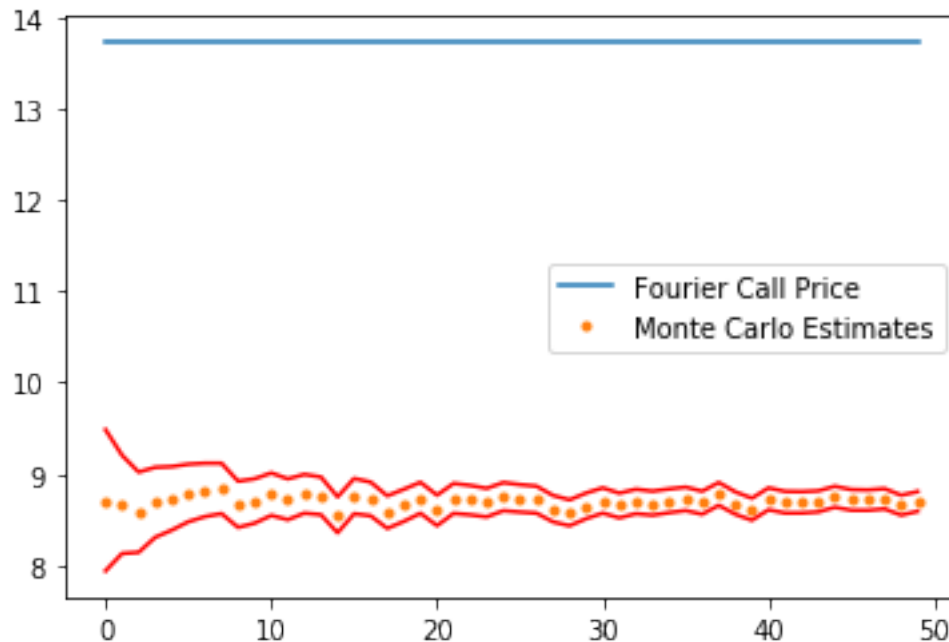
We plot the prices of our Monte Carlo estimates against the CEV noncentral chi-squared distribution prices calculated from Part 1 above:

```
[18]: plt.plot([cev_call_price]*50, label='CEV Call Price')
plt.plot(price_estimate, '.', label='Monte Carlo Estimates')
plt.plot(price_estimate + 3*np.array(price_std), 'r')
plt.plot(price_estimate - 3*np.array(price_std), 'r')
plt.legend()
plt.show()
```



We also plot the prices of our Monte Carlo estimates against the Fourier Call prices calculated from Part 1 above:

```
[19]: plt.plot([fourier_call_val]*50, label='Fourier Call Price')
plt.plot(price_estimate, '.', label='Monte Carlo Estimates')
plt.plot(price_estimate + 3*np.array(price_std), 'r')
plt.plot(price_estimate - 3*np.array(price_std), 'r')
plt.legend()
plt.show()
```



We notice that there is a discrepancy. Upon further investigation, for the Heston model, $v_0 = 0.06$ ($v_0 = \text{stock volatility}^2$), so stock volatility = $.06^{.5} = 0.2449$. Note that sigma under Heston model refers to volatility of stock volatility

Under our stock price Monte Carlo calculation, the default stock volatility is 0.0948 (given by $0.3(100)^{-.25}$). Thus its much less than Heston. To have the same initial stock volatility, we find a new value for σ by equating $\sigma(S_{ti})^{\gamma-1} = \sqrt{0.06}$, giving us $\sigma = 0.775$.

We then find that our newly calculated Monte Carlo calculated call prices are aligned with the Fourier prices.

```
[20]: sigma_const = 0.775

T = 1
sample_sizes = range(1000, 50001, 1000)

share_price_paths = {}

print("Start generating share price path")
start = time.time()
for sample_size in sample_sizes:
    share_val = generate_share_price_path(S0, r, T, sigma_const, gamma,
    ↪sample_size, timesteps, varying_vol=False)

    share_price_paths[sample_size] = share_val
    #print("Updated for sample size {} at {}".format(sample_size, datetime.
    ↪datetime.now().strftime('%H:%M')))
```

```

end = time.time()
print(f"Generating all samples paths takes {(end - start):.2f}s")

```

Start generating share price path
Generating all samples paths takes 2.10s

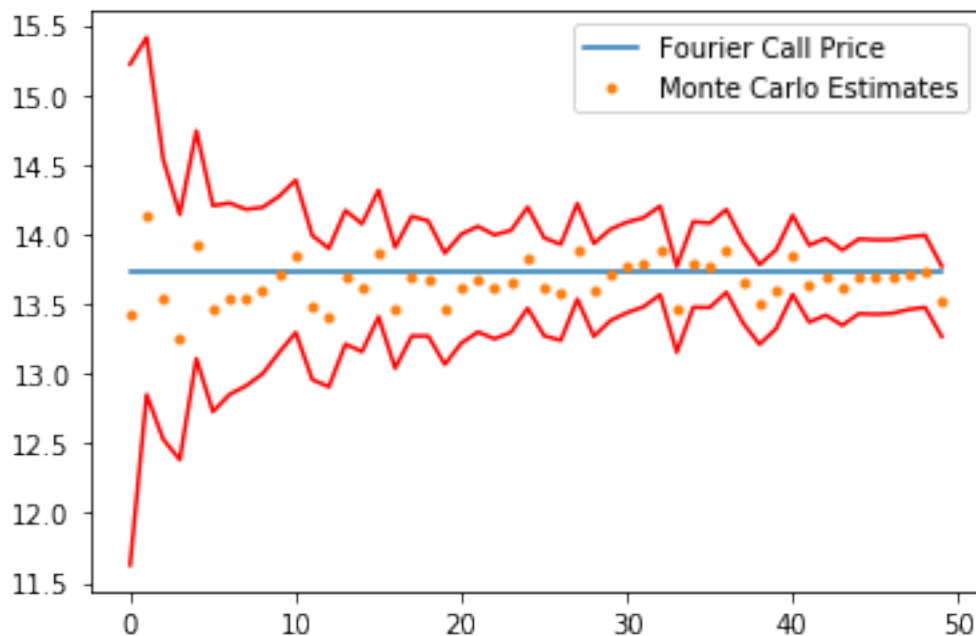
```

[21]: price_estimate = []
      price_std = []

      for size in sample_sizes:
          S_Ts = share_price_paths[size].iloc[12, :]
          payoff = np.maximum(S_Ts - K, 0)
          discounted_price = np.exp(-r*T)*payoff
          price_estimate.append(discounted_price.mean())
          price_std.append(discounted_price.std()/np.sqrt(size))

[22]: plt.plot([fourier_call_val]*50, label='Fourier Call Price')
      plt.plot(price_estimate, '.', label='Monte Carlo Estimates')
      plt.plot(price_estimate + 3*np.array(price_std), 'r')
      plt.plot(price_estimate - 3*np.array(price_std), 'r')
      plt.legend()
      plt.show()

```



5 Conclusion

References

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