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Pricing Stock Options in Mergers and Acquisitions with Jump-diffusion Model

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Abstract — We develop a jump-diffusion model to price options on the stocks involved in mergers and acquisitions. The test results indicate that our model performs well in explaining observed option prices. The model can be used by risk arbitrageurs to control risks associated with merger deals using options.

Key words: mergers and acquisitions, option pricing, jump diffusion, risk arbitrage

I. INTRODUCTION

There are extensive researches on the behavior of implied volatilities around merger or acquisition announcements ([5], [11], [12]), empirical studies of excess return of risk arbitrage in merger and acquisitions ([1], [7], [10]), and investigations on the informational content of speculation spread ([2], [6]).

There has been little work done so far in valuing options on the stocks of firms involved in a merger deal. Barone-Adesi, Brown, and Harlow [3] used option prices of the bidder and especially the target to predict the market's expectation of merger deal's consummation. However, their objective was not to build a pricing model. Subramanian [14] developed a theoretical framework in valuing options on the stocks of firms involved in a merger deal after the merger announcement and before the deal either goes through or is called off. In his model the jump size is a monotonic function of time, which is inconsistent with the market observations.

In this paper, a jump-diffusion model to determine the option prices when a merger or acquisition deal is pending is developed in section II. Section III shows the results of numerical implementation. Section IV concludes this paper.

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II. A JUMP DIFFUSION MODEL

A. Model Setup

We consider a probability space (Ω, F, P) equipped with a complete, right continuous filtration $\{F_t\}$. We assume that the probability space is large enough to accommodate four F_t-adapted Wiener processes W_1, W_2, W_3, W_4, and two F_t-adapted single jump processes Q_1, Q_2. The jump processes Q_1 and Q_2 are independent of the Brownian motions and have identical parameter λ. The Brownian Motions W_1, W_2 are independent of each other and the Brownian Motions W_3, W_4. However, W_3 and W_4 may have a nonzero correlation.

For simplicity, we assume the stocks pay no dividend. Let S_1 and S_2 be the underlying asset prices of the acquirer and target company. Before the deal is announced and after the deal is called off, the stock prices are assumed to satisfy the Black-Scholes model:

$$dS_1 = \mu_1' S_1 dt + \sigma_1'' S_1 dW_3 \tag{1}$$

$$dS_2 = \mu_2' S_2 dt + \sigma_2'' S_2 dW_4 \tag{2}$$

$$dW_3 dW_4 = \rho dt \tag{3}$$

Where μ_1' and μ_2' are the instantaneous expected return on stock of the acquirer and target company; σ_1'' and σ_2'' are the instantaneous variance of the return; ρ is the correlation between W_3 and W_4; $\mu_1', \mu_2', \sigma_1'', \sigma_2'', \rho$ are assumed to be constant and $-1 < \rho < 1$.

We assume that a merger or acquisition announcement is made at time t = 0 and the deal is expected to go through at the time horizon T. However, there is a nonzero probability that the deal could be called off at some time in the interval [0, T) and the effects of this breakdown process are the jump processes Q_1 and Q_2. The jump sizes are random variables Y_1 and Y_2. The risk-neutral probability that the deal is called off during a time interval $[t, t+dt] \subset [0, T)$ provided it has not yet been called off is λdt. Therefore, the risk-neutral probability that the deal will be called off at some time before the deal date is $1-\exp(-\lambda T)$. The risk-neutral probability that there is no jump in $[0, T)$, or alternatively the risk-neutral probability that the deal is successful, is $\exp(-\lambda T)$.

We consider the scenario where the terms of the merger deal are such that each shareholder of the target firm will receive α alpha share of the stock of the acquirer firm. If the deal goes through, we have

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$$S_2(T) = \alpha S_1(T) \quad (4)$$

We also assume that the terms of the merger deal allow an option with maturity τ and strike K of the target company to be exchanged for α option with maturity τ and strike K/α of the acquirer company when the deal goes through.

The two stock price processes when the merger has been announced and has not yet been called off are assumed to satisfy:

$$dS_1 = \mu_1 S_1 dt + \sigma_1 S_1 dW_1 + dQ_1 \quad (5)$$

$$dS_2 = \mu_2 S_2 dt + \sigma_2 S_2 dW_1 + \sigma_2' S_2 dW_2 + dQ_2 \quad (6)$$

Where μ_1 and μ_2 are the instantaneous expected return; σ_1, σ_2 and σ_2' are the instantaneous variance of the return; $\mu_1, \mu_2, \sigma_1, \sigma_2, \sigma_2'$ are assumed to be constant; dQ_1 and dQ_2 are single jump processes with identical parameter λ.

Under the risk-neutral measure, we must have

$$\mu_1' = \mu_2' = r$$

$$\mu_1 = r - \lambda k_1$$

$$\mu_2 = r - \lambda k_2$$

where r is the risk-free interest rate; $k_i \equiv E(Y_i - 1)$ where (Y_i -1) is the percentage change in the stock price if the jump process occurs, i = 1, 2; and E is the expectation operator over the random variables Y_1 and Y_2. As in Subramanian [14], it is straightforward to show that $\sigma_1 = \sigma_2$ and $\sigma_2' = 0$ (see appendix A for proof).

In summary, S_1 and S_2 satisfy the following stochastic differential equations under the risk-neutral probability for $0 \le t < T$,

$$dS_1 = 1_{\{N(t)=0\}}\left[(r - \lambda k_1)S_1 dt + \sigma_1 S_1 dW_1\right] + 1_{\{N(t)=1\}}\left[rS_1 dt + \sigma_1'' S_1 dW_3\right] + dQ_1 \quad (7)$$

$$dS_2 = 1_{\{N(t)=0\}}\left[(r - \lambda k_2)S_2 dt + \sigma_1 S_2 dW_1\right] + 1_{\{N(t)=1\}}\left[rS_2 dt + \sigma_2'' S_2 dW_4\right] + dQ_2 \quad (8)$$

where $N(t)=0$ represents the scenario when the jump has not occurred and $N(t)=1$ represents the scenario when the jump has occurred.

B. Pricing of European Option

First we consider the pricing of European call options that expires before the expected merger deal closing date (i.e., maturity time $\tau < T$) only. The pricing of longer maturities options (i.e., $\tau > T$) could be determined by similar analysis.

Suppose that both option price H_1 of the acquirer company and option price H_2 of the target company can be written as a twice-continuously differentiable function of the stock price and time. Using Ito's Lemma for the continuous part and an analogous lemma for the jump part (see, for example, [13 chapter 6]), then option prices where the deal has not been called off (i.e., the jump has not occurred) satisfies the following dynamics:

$$dH_1(S_1,t) = \Big(H_{1t}(S_1,t) + H_{1S}(S_1,t)(r - \lambda k_1)S_1 + \frac{1}{2}\sigma_1^2 S_1^2 H_{1SS}(S_1,t) + \lambda E\big(H_1(S_1Y_1,t) - H_1(S_1,t)\big)\Big)dt + H_{1S}(S_1,t)\sigma_1 S_1 dW_1 + dQ_{H1} \quad (9)$$

$$dH_2(S_2,t) = \Big(H_{2t}(S_2,t) + H_{2S}(S_2,t)(r - \lambda k_2)S_2 + \frac{1}{2}\sigma_1^2 S_2^2 H_{2SS}(S_2,t) + \lambda E\big(H_2(S_2Y_2,t) - H_2(S_2,t)\big)\Big)dt + H_{2S}(S_2,t)\sigma_1 S_2 dW_1 + dQ_{H2} \quad (10)$$

We form a portfolio P_1 with stock and option of the target company as $H_1 + \varpi_1 S_1$. The portfolio P_1 has the following dynamics

$$dP_1 = \Big(H_{1t} + (H_{1S} + \varpi_1)rS_1 - \lambda k_1 S_1 H_{1S} + \frac{1}{2}\sigma_1^2 S_1^2 H_{1SS} + \lambda E\big(H_1(S_1Y_1,t) - H_1(S_1,t)\big)\Big)dt + (H_{1S} + \varpi_1)\sigma_1 S_1 dW_1 + dH_{1\,jump} + \varpi_1 dQ_1 \quad (11)$$

In our model setup, the source of the jumps is merger-related information, which represents 'non-systematic' risk. Setting $\varpi_1 = -H_{1S}$ will eliminate the systematic risk from the portfolio and thus the beta of the portfolio will be zero. As suggested in Merton [9], if the Capital Asset Pricing model holds, then the expected return on all zero-beta securities must equal the risk-free rate. Thus, we have

$$H_{1t} + \frac{1}{2}\sigma_1^2 S_1^2 H_{1SS} - rH_1 + (r - \lambda k_1)S_1 H_{1S} + \lambda E\big(H_1(S_1Y_1,t) - H_1(S_1,t)\big) = 0 \quad (12)$$

subject to the boundary conditions

$$H_1(0,t) = 0, \quad H_1(S_1,\tau) = \max[0, S_1 - K] \quad (13)$$

where K is the strike of the option.

Define $F(S,\tau;K,r,\sigma^2)$ to be the Black-Scholes option pricing formula [4]. F can be written as

$$F(S,\tau;K,r,\sigma^2) = SN(d_1) - K\exp(-r\tau)N(d_2),$$

where

$$N(y) \equiv \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y} \exp(-s^2/2)ds,$$

the cumulative normal distribution function,

$$d_1 = \frac{\log(S/K) + (r + \sigma^2/2)\tau}{\sigma\sqrt{\tau}},$$

and

$$d_2 = d_1 - \sigma\sqrt{\tau}.$$

Note that there is either exactly one jump or no jump at all. Therefore the value of $H_1(S_1,\tau)$ has two components. The first component represents the possibility that the deal is not called off. The value of the first component is $\exp(-\lambda\tau)F(S_1,\tau;K,r - \lambda k_1,\sigma_1^2)$. The second component represents the possibility that the deal is called off.

Recall that the risk neutral probability that the deal is called off at $0 < s < \tau$ is $\lambda\exp(-\lambda s)$. Therefore,

$$S_1(s-) = S_1(0)\exp\left[\int_0^s \left(r - \lambda k_1 - (1/2)\sigma_1^2\right)dt + \sigma_1\int_0^s dW_1(t)\right] \quad (14)$$

Since $S_1(s) = Y_1 S_1(s-)$, we have

$$S_1(\tau) = S_1(s-)Y_1 \exp\left[\left(r-(1/2)\sigma_1''^2\right)(\tau - s) + \sigma_1'' W_3(\tau - s)\right]$$
$$= S_1(0)\exp\left[\left(r - \lambda k_1 - (1/2)\sigma_1^2\right)s + \sigma_1 W_1(s)\right]Y_1 \cdot$$
$$\exp\left[\left(r-(1/2)\sigma_1''^2\right)(\tau - s) + \sigma_1'' W_3(\tau - s)\right] \qquad (15)$$

Thus, value of second component is

$$\exp(-r\tau)\int_0^\tau ds\, \lambda \exp(-\lambda s) E\Big[\Big(S_1(0)Y_1 \exp\Big[\left(r - \lambda k_1 - (1/2)\sigma_1^2\right)s$$
$$+ \sigma_1 W_1(s) + (r-(1/2)\sigma_1''^2)(\tau - s) + \sigma_1'' W_3(\tau - s)\Big] - K\Big)^+\Big] \qquad (16)$$

Assume Y_1 follows log-normal distribution, specifically $\log(Y_1)$ follows $N(\log(k_1+1)+\delta_1^2/2, \delta_1^2)$. We replace W_3 with W_1 as they are independent. Also note that the jump processes are independent with W_1. Then (16) becomes

$$\exp(-r\tau)\int_0^\tau ds\, \lambda \exp(-\lambda s) E\Big[\Big(S_1(0) \exp\Big[\left(r - \lambda k_1 - (1/2)\sigma_1^2\right)s$$
$$+ (r-(1/2)\sigma_1''^2)(\tau - s) + \log(1+k_1)$$
$$+ \sigma_1 W_1(s) + \sigma_1'' W_1(\tau - s) + W_1\left(\delta_1^2\right)\Big] - K\Big)^+\Big] \qquad (17)$$

After taking integral (see Appendix B), finally we have

$$S_1(0)\int_0^\tau \lambda \exp(-\lambda s) N(\alpha_1) ds - \exp(-r\tau) K \int_0^\tau \lambda \exp(-\lambda s) N(\alpha_1') ds \qquad (18)$$

where

$$\alpha_1 = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1+k_1) + (1/2)\left(\sigma_1^2 s + \sigma_1''^2(\tau - s)\right)}{\sqrt{\left(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2\right)}}$$

$$\alpha_1' = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1+k_1) - (1/2)\left(\sigma_1^2 s + \sigma_1''^2(\tau - s)\right)}{\sqrt{\left(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2\right)}}$$

In most merger deals, the equity size of the acquirer company is significantly larger than that of the target company. It is reasonable to assume that even if the merger is called off, it will not change the variance of stock process, which indicates $\sigma_1'' = \sigma_1$. Then α_1 and α_1' could be simplified to

$$\alpha_1 = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1+k_1) + (1/2)\sigma_1^2 \tau}{\sqrt{\left(\sigma_1^2 \tau + \delta_1^2\right)}}$$

$$\alpha_1' = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1+k_1) - (1/2)\sigma_1^2 \tau}{\sqrt{\left(\sigma_1^2 \tau + \delta_1^2\right)}}$$

Combining first component with second component, we have $H_1(S_1, \tau; K, r, \sigma_1^2, \lambda, k_1, \delta^2)$

$$= \exp(-\lambda\tau) F\left(S_1, \tau; K, r - \lambda k_1, \sigma_1^2\right)$$
$$+ S_1(0)\int_0^\tau \lambda \exp(-\lambda s) N(\alpha_1) ds - \exp(-r\tau) K \int_0^\tau \lambda \exp(-\lambda s) N(\alpha_1') ds$$

Usually $\sigma_2'' = \sigma_1$ does not hold for the target company. However, using similar analysis we would still be able to derive the solution for $H_2(S_2, \tau; K, r, \sigma_1^2, \sigma_2'', \lambda, k_2, \delta_2^2)$.

III. NUMERICAL IMPLEMENTATION AND RESULTS

A. Data Description

The data set consisting daily stock and option price data was obtained from TBSP Inc. For each deal and for each day, we collect the closing price for the stocks, closing bid and ask prices for the options. The options we use have a maturity date earlier than the expected deal completion date. We pick call and put options with strike prices at or near the strike price, and strike prices immediately above and below this strike price.

The data on the daily Treasure-bill yield are obtained from Department of Treasure (www.treas.gov). For convenience, the Treasure-bill yield whose maturity date is closest to the option maturity date is used in the computation.

B. Implementation and Methodology

The model has eight basic parameters that are described below.

σ_1'' : Volatility of stock 1 after the deal has been called off

σ_2'' : Volatility of stock 2 after the deal has been called off

σ_1 : Volatility of both stocks when the deal is pending

λ : Parameter of jump process

k_1, k_2 : Mean of the percentage change in the stock price

γ_1, γ_2 : Standard deviation of the logarithm of the jump size

The parameters σ_1'' and σ_2'' is chosen to be the at-the-money implied volatilities 3 months before the deal was announced.

The other parameters of the model are calibrated to the market prices of the multiple options on both the stocks of varying strikes and maturities. We calculate the model parameters to minimize the sum of the magnitudes of the differences between the actual option prices and those predicted by the model. Specifically, we find $(\sigma_1, \lambda, k_1, k_2, \gamma_1, \gamma_2)$ that minimizes

$$\sum_{n=1}^{N} \frac{\left|H_n(t, \tau_n, K_n) - \hat{H}_n(t, \tau_n, K_n)\right|}{\hat{H}_n(t, \tau_n, K_n)} \qquad (19)$$

where N is the total number of options on both stocks, $H_n(t, \tau_n, K_n)$ is the theoretical price predicted by the model for ith option, $\hat{H}_n(t, \tau_n, K_n)$ is the observed price for ith option.

The calibrated parameters are then used to predict theoretical prices for the options. This would also enable us to examine the model's out-of-sample cross-sectional pricing performance. For this purpose, we rely on previous day's option prices to back out the parameter values and then use them as input to compute current day's model-based option prices. Equation (19) is used to compute percentage pricing error.

Following Merton [8], the dividends are treated as a continuous yield in the implementation. Since equity options in the U.S. market are American and not European, we implement our model numerically using the standard binomial tree-based methodology to derive theoretical American option prices.

C. Results

Target	Acquirer	In-Sample Mean Model Error	In-Sample Stdev Model Error	Out-of-Sample Mean Model Error	Out-of-Sample Stdev Model Error
MCDT	BRCD	1.21%	0.14%	18.14%	3.54%
VRTS	SYMC	0.94%	0.11%	14.94%	2.63%
PIXR	DIS	0.70%	0.08%	10.10%	1.89%
MXO	STX	0.84%	0.10%	12.29%	2.47%
SILI	VSH	0.75%	0.10%	17.21%	3.31%
STCR	QTWW	1.17%	0.12%	16.78%	2.91%
RDN	MTG	1.02%	0.15%	17.82%	4.24%

Table 1. Summarized Results

Table 1 presents the summarized results of the tests. For each deal, we display both in-sample and out-of-sample mean percentage error. Although our model performs very well for in-sample fitting, it is plausible that it is a consequence of having a large number of structural parameters. Considering that the bid-ask spreads in the prices of most options are very close to 10%, the results of out-of-sample pricing are acceptable. For out-of-sample pricing, the presence of more parameters may actually cause over-fitting and have the model penalized if the extra parameters do not improve its structural fitting.

IV. CONCLUSIONS

We develop a jump-diffusion model to price options on the stocks involved in mergers and acquisitions. We assume parameter λ to be constant and the jump size follows log-normal distribution. Although empirical studies ([2], [6]) indicate that both possibility of deal success and jump size are correlated with speculation spread and it is not perfectly consistent with our model assumptions, our test results show that our model performs well in explaining observed option prices. The model can be used by risk arbitrageurs to control risks associated with merger deals using options.

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APPENDIX

A. Proof of $\sigma_1 = \sigma_2$ and $\sigma_2' = 0$.

Let $\beta(t) = S_2(t)/S_1(t)$. We consider the situation when the jump does not occur. From equation (5), (6), $\mu_1 = r - \lambda k_1$ and $\mu_2 = r - \lambda k_2$, we must have

$$\beta(t) = \beta(0)\exp\Big[\Big(\lambda k_1 - \lambda k_2 + \frac{1}{2}(\sigma_2 - \sigma_1)^2 - \frac{1}{2}\left(\sigma_2^2 - \sigma_1^2\right) - \frac{1}{2}\sigma_2'^2\Big)t$$
$$+ (\sigma_2' - \sigma_1')W_1(t) + \sigma_2''^2 W_2(t)\Big]$$

When the deal goes through, we also have $\beta(T) = \alpha$ where α is the stock for stock exchange ratio of the merger deal. Therefore

$$\log(\alpha/\beta(0)) = \Big(\lambda k_1 - \lambda k_2 + \frac{1}{2}(\sigma_2 - \sigma_1)^2 - \frac{1}{2}\left(\sigma_2^2 - \sigma_1^2\right) - \frac{1}{2}\sigma_2'^2\Big)T$$
$$+ (\sigma_2 - \sigma_1)W_1(T) + \sigma_2'^2 W_2(T)$$

Since $k_1, k_2, \sigma_1, \sigma_2, \sigma_2', \alpha, \beta(0)$ are constants, thus $(\sigma_2 - \sigma_1)W_1(T) + \sigma_2''^2 W_2(T)$ is bounded. Therefore, we must have $\sigma_1 = \sigma_2$ and $\sigma_2' = 0$ as W_1 and W_2 are independent Wiener processes.

Q.E.D

B. Derivation of equation (18)

$$\exp(-r\tau)\int_0^\tau ds\,\lambda\exp(-\lambda s)E\Big[\Big(S_1(0)\exp\Big[\left(r - \lambda k_1 - (1/2)\sigma_1^2\right)s$$
$$+ (r - (1/2)\sigma_1''^2)(\tau - s) + \log(1 + k_1)$$
$$+ \sigma_1 W_1(s) + \sigma_1'' W_1(\tau - s) + W_1\left(\delta_1^2\right)\Big] - K\Big)^+\Big]$$
$$= \exp(-r\tau)\int_0^\tau ds\,\lambda\exp(-\lambda s)E\Big[\Big(S_1(0)\exp\Big[r\tau - \lambda k_1 s - (1/2)\sigma_1^2 s$$
$$- (1/2)\sigma_1''^2(\tau - s) + \log(1 + k_1)$$
$$+ W_1\left(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2\right)\Big] - K\Big)^+\Big]$$

Setting $P = S_1(0)\exp\Big[r\tau - \lambda k_1 s - (1/2)\sigma_1^2 s - (1/2)\sigma_1''^2(\tau - s)$
$+ \log(1 + k_1) + W_1\left(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2\right)\Big]$

Above

$$= \exp(-r\tau)\int_0^\tau ds\,\lambda\exp(-\lambda s)\int_K^\infty \frac{1}{\sqrt{2\pi(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)}}(P - K)$$
$$\exp\left(-\frac{\left(\log(P/S_1(0)) - r\tau - \lambda k_1 s - \log(1 + k_1) + (1/2)\sigma_1^2 s + (1/2)\sigma_1''^2(\tau - s)\right)^2}{2\left((\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)\right)}\right)\frac{dP}{P}$$
$$= \exp(-r\tau)\int_0^\tau ds\,\lambda\exp(-\lambda s)\int_K^\infty \frac{1}{\sqrt{2\pi(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)}}$$
$$\exp\left(-\frac{\left(\log(P/S_1(0)) - r\tau - \lambda k_1 s - \log(1 + k_1) + (1/2)\sigma_1^2 s + (1/2)\sigma_1''^2(\tau - s)\right)^2}{2\left((\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)\right)}\right)dP$$
$$- K\exp(-r\tau)\int_0^\tau ds\,\lambda\exp(-\lambda s)\int_K^\infty \frac{1}{\sqrt{2\pi(\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)}}$$
$$\exp\left(-\frac{\left(\log(P/S_1(0)) - r\tau - \lambda k_1 s - \log(1 + k_1) + (1/2)\sigma_1^2 s + (1/2)\sigma_1''^2(\tau - s)\right)^2}{2\left((\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)\right)}\right)\frac{dP}{P}$$
$$= S_1(0)\int_0^\tau \lambda\exp(-\lambda s)N(\alpha_1)ds - \exp(-r\tau)K\int_0^\tau \lambda\exp(-\lambda s)N(\alpha_1')ds$$

where

$$\alpha_1 = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1 + k_1) + (1/2)\left(\sigma_1^2 s + \sigma_1''^2(\tau - s)\right)}{\sqrt{\left((\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)\right)}}$$
$$\alpha_1' = \frac{\log(S_1(0)/K) + r\tau - \lambda k_1 s + \log(1 + k_1) - (1/2)\left(\sigma_1^2 s + \sigma_1''^2(\tau - s)\right)}{\sqrt{\left((\sigma_1^2 s + \sigma_1''^2(\tau - s) + \delta_1^2)\right)}}$$

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