

RETRIEVING LÉVY PROCESSES FROM OPTION PRICES: REGULARIZATION OF AN ILL-POSED INVERSE PROBLEM*

RAMA CONT[†] AND PETER TANKOV[‡]

Abstract. We propose a stable nonparametric method for constructing an option pricing model of exponential Lévy type, consistent with a given data set of option prices. After demonstrating the ill-posedness of the usual and least squares version of this inverse problem, we suggest to regularize the calibration problem by reformulating it as the problem of finding an exponential Lévy model that minimizes the sum of the pricing error and the relative entropy with respect to a prior exponential Lévy model. We prove the existence of solutions for the regularized problem and show that it yields solutions which are continuous with respect to the data, stable with respect to the choice of prior, and which converge to the minimum entropy least squares solution of the initial problem when the noise level in the data vanishes.

Key words. inverse problem, entropy, Lévy process, jump process, model calibration, option pricing, regularization, ill-posed problem

AMS subject classifications. 49N45, 60G51, 60J75, 91B70

DOI. 10.1137/040616267

1. Introduction. The specification of an arbitrage-free option pricing model on a time horizon T_∞ involves the choice of a *risk-neutral* measure [25]: a probability measure Q on the set Ω of possible trajectories $\{S_t\}_{t \in [0, T_\infty]}$ of the underlying asset such that the discounted asset price $e^{-rt}S_t$ is a martingale (where r is the discount rate). Such a probability measure Q then specifies a pricing rule which attributes to an option with terminal payoff H_T at T the value $C(H_T) = e^{-rT}E^Q[H_T]$. For example, the value under the pricing rule Q of a call option with strike K and maturity T is given by $e^{-rT}E^Q[(S_T - K)^+]$. Given that data sets of option prices have become increasingly available, a common approach for selecting the pricing model is to choose, given option prices $(C(H^i))_{i \in I}$ with maturities T_i payoffs H^i , a risk-neutral measure Q compatible with the observed market prices, i.e., such that $C(H^i) = e^{-rT_i}E^Q[H^i]$. This *inverse problem* of determining a pricing model Q verifying these constraints is known as the “model calibration” problem. The number of observed options can be large ($\simeq 100$ – 200 for index options) and the Black–Scholes model has to be replaced with models with richer structure such as nonlinear diffusion models [18] or models with jumps [13]. The inverse problem is ill-posed in these settings [14, 33] and various methods have been proposed for solving it in a stable manner, mostly in the framework of diffusion models [1, 4, 5, 6, 9, 16, 18, 26, 28, 32, 33].

Given the ill-posed nature of the inverse problem, an extra criterion must be used to select a model compatible with observed option prices. The use of *relative entropy* as a model selection criterion has solid theoretical foundations [17] and has been investigated by many authors in the context of option pricing.

*Received by the editors October 4, 2004; accepted for publication (in revised form) August 4, 2005; published electronically February 15, 2006.

<http://www.siam.org/journals/sicon/45-1/61626.html>

[†]CMAP–Ecole Polytechnique, F 91128 Palaiseau, France (Rama.Cont@polytechnique.org, Peter).

[‡]Laboratoire de Probabilités et Modèles Aléatoires, Université de Paris VII, 2, Place Jussieu, 75251 Paris, France (Tankov@polytechnique.org). This author was supported by an AMX fellowship from the French Ministry of Education.

The notion of minimal entropy martingale measure (MEMM)—the pricing measure Q that minimizes the relative entropy with respect to a reference probability P —has been investigated by many authors [22, 19, 29]. However, option prices computed using the MEMM are in general not consistent with the market-quoted prices of traded European options and can lead to arbitrage opportunities with respect to market-traded options.

The notion of minimal entropy distribution consistent with observed market prices was introduced in a static framework in [4, 3, 35]; given prices of call options $\{C_M(T_i, K_i)\}_{i \in I}$ and a prior distribution P on scenarios, it is obtained by minimizing relative entropy over all probability measures $Q \sim P$ such that

$$(1.1) \quad C_M(T_i, K_i) = E^Q[e^{-rT_i}(S_{T_i} - K_i)^+] \text{ for } i \in I.$$

This approach is based on relative entropy minimization under constraints [17] and yields a computable result. It was extended to the case of stochastic processes by the weighted Monte Carlo method of Avellaneda et al. [5], but the martingale property is not taken into account since it would yield an infinite number of constraints [30]. As a result, derivative prices computed with the weighted Monte Carlo algorithm may contain arbitrage opportunities, especially when applied to forward start contracts.

Goll and Rüschemdorf [24] consider the notion of consistent (or calibrated) MEMM (CMEMM), defined as the solution of

$$I(Q^*|P) = \min_{Q \in \mathcal{M}^*} I(Q|P),$$

where the minimum is taken over all martingale measures $Q \sim P$ verifying (1.1). While this notion seems to conciliate the advantages of the MEMM and Avellaneda's entropy minimization under constraints, no algorithm is proposed in [24] to compute the CMEMM. In fact, the notion of CMEMM does not in general preserve the structure of the prior—e.g., the Markov property—and it may be difficult to represent.¹

We also note that such model selection methods based on relative entropy are not convenient when dealing with one-dimensional diffusion models since as soon as the model has a diffusion coefficient different from the prior their measures become singular and the relative entropy is infinite.

In this paper we show that the shortcomings of the above approaches can be overcome by enlarging the class of models to include processes with jumps and using relative entropy as a regularization criterion rather than a selection criterion. On one hand, introducing jumps in the prior model allows us to obtain a large class of equivalent martingale measures which also have finite relative entropy with respect to the prior, avoiding the singularity which arises in diffusion models. On the other hand, by restricting the class of pricing models to exponential Lévy models—where the risk-neutral dynamics of the logarithm of the stock price is given by a Lévy process—we are able to go beyond a simple existence result and obtain a computable alternative to the CMEMM. Also, unlike the weighted Monte Carlo approach, our approach yields as a solution a continuous-time price process whose discounted value is a martingale. Finally, the use of regularization yields a stable solution to the inverse problem for which a computational approach is possible [14].

The relation between the option prices and the parameters of the process (its Lévy measure) being nonlinear, we face a nonlinear, infinite-dimensional inverse problem.

¹In particular, if X is a Lévy process under the prior P , it will in general no longer be a Lévy process under a consistent MEMM.

After demonstrating the ill-posedness of the usual and least squares version of this inverse problem, we show that it can be regularized by using as a penalization term the relative entropy with respect to a prior exponential Lévy model. We show that our approach yields solutions which are continuous with respect to the data, stable with respect to the choice of prior, and which converge to the minimum entropy least squares solution of the initial problem.

Unlike linear inverse problems for which general results on regularization methods and their convergence properties are available [20], nonlinear inverse problems have been explored less systematically. Our study is an example of rigorous analysis of regularization using entropy for a nonlinear, infinite-dimensional inverse problem. Previous results on regularization using entropy have been obtained in a Banach space setting [21] by mapping the problem to a Tikhonov regularization problem. Using probabilistic methods, we are able to use a direct approach and extend these results to the spaces of probability measures considered here.

The paper is structured as follows. Section 2 recalls basic facts about Lévy processes and exponential Lévy models. In section 3 we formulate the calibration problem as that of finding a martingale measure Q , consistent with market-quoted prices of traded options, under which the logarithm of the stock price process remains a Lévy process. We show that both this problem and its least squares version are ill-posed: a solution need not exist and, when it exists, may be unstable with respect to perturbations in the data. Section 4 discusses relative entropy in the case of Lévy processes and its use as a criterion for selecting solutions, and introduces the notion of minimum entropy least squares solution. In section 5 we formulate the regularized version of the calibration problem, show that it always admits a solution depending continuously on market data, discuss conditions for the solutions to be equivalent martingale measures, and formulate conditions under which they converge to the minimum entropy least squares solutions as the noise level in the data goes to zero.

In section 6 we show that the solutions of the regularized calibration problem are stable with respect to small perturbations of the prior measure. The solutions of the regularized calibration problem with any prior measure can thus be approximated (in the weak sense) by the solutions of regularized problems with discretized priors, which has implications for the discretization and the numerical solution of the regularized calibration problem, further discussed in [14]. In the appendix we discuss some properties of relative entropy in the case of Lévy processes.

2. Definitions and notation. Consider a time horizon $T_\infty < \infty$ and denote by Ω the space of real-valued cadlag functions on $[0, T_\infty]$, equipped with the Skorokhod topology [27]. The time horizon T_∞ must be chosen finite since we will work with the class of Lévy processes absolutely continuous with respect to a given Lévy process, and on an infinite time interval this class is trivial since in this case absolute continuity of Lévy processes is equivalent to identity in law [27, Theorem IV.4.39]. Unless otherwise mentioned, X is the coordinate process: for every $\omega \in \Omega$, $X_t(\omega) := \omega(t)$. \mathcal{F} is the smallest σ -field, for which the mappings $\omega \in \Omega \mapsto \omega(s)$ are measurable for all $s \in [0, T_\infty]$ and for any $t \in [0, T_\infty]$, and (\mathcal{F}_t) is the natural filtration of $(X_t)_{t \in [0, T_\infty]}$. Weak convergence of measures will be denoted by \Rightarrow .

Lévy processes. A Lévy process $\{X_t\}_{t \geq 0}$ on (Ω, \mathcal{F}, P) is a stochastic process with stationary independent increments satisfying $X_0 = 0$. The characteristic function of X_t has the following form, called the Lévy–Khinchin representation [34]:

$$(2.1) \quad E[e^{izX_t}] = e^{t\psi(z)} \text{ with } \psi(z) = -\frac{1}{2}Az^2 + i\gamma z + \int_{-\infty}^{\infty} (e^{izx} - 1 - izh(x))\nu(dx),$$

where $A \geq 0$ is the unit variance of the Brownian motion part of the Lévy process, $\gamma \in \mathbb{R}$, ν is a positive measure on \mathbb{R} verifying $\nu(\{0\}) = 0$ and

$$\int_{-\infty}^{\infty} (x^2 \wedge 1) \nu(dx) < \infty,$$

and h is the truncation function: any bounded measurable function $\mathbb{R} \rightarrow \mathbb{R}$ such that $h(x) \equiv x$ on a neighborhood of zero. The most common choice of truncation function is $h(x) = x1_{|x| \leq 1}$ but sometimes in this paper we will need h to be continuous. The triplet (A, ν, γ) is called the characteristic triplet of X with respect to the truncation function h .

Model setup. We consider exponential Lévy models, where the stock price S_t is modeled, under a *risk-neutral measure* Q [25], as the exponential of a Lévy process:

$$(2.2) \quad S_t = S_0 e^{rt + X_t},$$

where r is the interest rate. Since Q is a risk-neutral probability measure, e^{X_t} must be a martingale. It follows from (2.1) that this is the case if and only if

$$(2.3) \quad \frac{A}{2} + \gamma + \int_{-\infty}^{\infty} (e^x - 1 - h(x)) \nu(dx) = 0.$$

Under Q call option prices can be evaluated as discounted expectations of terminal payoffs:

$$(2.4) \quad C^Q(T, K) = e^{-rT} E^Q[(S_T - K)^+] = e^{-rT} E^Q[(S_0 e^{rT + X_T} - K)^+].$$

Notation. In what follows $\mathcal{P}(\Omega)$ denotes the set of probability measures (stochastic processes) on (Ω, \mathcal{F}) , \mathcal{L} denotes the set of all probability measures $P \in \mathcal{P}(\Omega)$ under which the coordinate process X is a Lévy process, and \mathcal{M} stands for the set of all probability measures $P \in \mathcal{P}(\Omega)$, under which $\exp(X_t)$ is a martingale. \mathcal{L}_{NA} is the set of all probability measures $P \in \mathcal{L}$ corresponding to arbitrage-free exponential Lévy models, that is, to Lévy processes that are not almost surely increasing nor almost surely decreasing. Furthermore, for $B > 0$ we define

$$\mathcal{L}_B^+ = \{P \in \mathcal{L}, P[\Delta X_t \leq B \forall t \in [0, T_\infty]] = 1\},$$

the set of Lévy processes with jumps bounded from above by B .

The following lemma shows the usefulness of the above definitions.

LEMMA 2.1. *The set $\mathcal{M} \cap \mathcal{L}_B^+$ is weakly closed for every $B > 0$.*

Proof. Let $\{Q_n\}_{n=1}^\infty \subset \mathcal{M} \cap \mathcal{L}_B^+$ with characteristic triplets (A_n, ν_n, γ_n) with respect to a continuous truncation function h and let Q be a Lévy process with characteristic triplet (A, ν, γ) with respect to h , such that $Q_n \Rightarrow Q$. Note that the limit in distribution of a sequence of Lévy processes is necessarily a Lévy process; due to convergence of characteristic functions, the limiting process must have stationary and independent increments. Define a function f by

$$f(x) := \begin{cases} 0, & x \leq B, \\ 1, & x \geq 2B, \\ \frac{x-B}{B}, & B < x < 2B. \end{cases}$$

By Corollary VII.3.6 in [27], $\int_{-\infty}^{\infty} f(x) \nu(dx) = \lim_{n \rightarrow \infty} \int_{-\infty}^{\infty} f(x) \nu_n(dx) = 0$, which implies that the jumps of Q are bounded by B . Define

$$g(x) := \begin{cases} e^x - 1 - h(x) - \frac{1}{2}h^2(x), & x \leq B, \\ e^B - 1 - h(B) - \frac{1}{2}h^2(B), & x > B. \end{cases}$$

Then, once again by Corollary VII.3.6 in [27] and because Q_n satisfies the martingale condition (2.3) for every n ,

$$\begin{aligned} \gamma + \frac{A}{2} + \int_{-\infty}^{\infty} (e^x - 1 - h(x))\nu(dx) &= \gamma + \frac{A + \int_{-\infty}^{\infty} h^2(x)\nu(dx)}{2} + \int_{-\infty}^{\infty} g(x)\nu(dx) \\ &= \lim_{n \rightarrow \infty} \left\{ \gamma_n + \frac{A_n + \int_{-\infty}^{\infty} h^2(x)\nu_n(dx)}{2} + \int_{-\infty}^{\infty} g(x)\nu_n(dx) \right\} = 0, \end{aligned}$$

which shows that Q also satisfies the condition (2.3). \square

3. The calibration problem and its least squares formulation. Suppose first that the market data C_M are consistent with the class of exponential Lévy models. This is, for example, the case when the market pricing rule is an exponential Lévy model but can hold more generally since many models may give the same prices for a given set of European options. For instance one can construct, using Dupire's formula [18], a diffusion model that gives the same prices, for a set of European options, as a given exp-Lévy model [12]. Using the notation defined in the preceding section, the calibration problem assumes the following form.

PROBLEM 1 (calibration with equality constraints). *Given prices of call options $\{C_M(T_i, K_i)\}_{i \in I}$, find an arbitrage-free exponential Lévy model $Q^* \in \mathcal{M} \cap \mathcal{L}$ such that*

$$(3.1) \quad \forall i \in I, \quad C^{Q^*}(T_i, K_i) = C_M(T_i, K_i).$$

When the market data are not consistent with the class of exponential Lévy models, the exact calibration problem may not have a solution. In this case one may consider an approximate solution: instead of reproducing the market option prices exactly, one may look for a Lévy triplet which reproduces them in a least squares sense. Let w be a probability measure on $[0, T_\infty] \times [0, \infty)$ (the weighting measure, determining the relative importance of different data points). An option data set is defined as a mapping $C : [0, T_\infty] \times [0, \infty) \rightarrow [0, \infty)$ and the data sets that coincide w -almost everywhere are considered identical. One can introduce a norm on option data sets via

$$(3.2) \quad \|C\|_w^2 := \int_{[0, T_\infty] \times [0, \infty)} C(T, K)^2 w(dT \times dK).$$

The quadratic pricing error in model Q is then given by $\|C_M - C^Q\|_w^2$. If the number of constraints is finite, then $w = \sum_{i=1}^N w_i \delta_{(T_i, K_i)}(dT \times dK)$ (with, e.g., N constraints), where $\{w_i\}_{1 \leq i \leq N}$ are positive weights that sum up to one. Therefore, in this case

$$(3.3) \quad \|C_M - C^Q\|_w^2 = \sum_{i=1}^N w_i (C_M(T_i, K_i) - C^Q(T_i, K_i))^2.$$

The following lemma establishes some useful properties of the pricing error functional.

LEMMA 3.1. *The pricing error functional $Q \mapsto \|C_M - C^Q\|_w^2$ is uniformly bounded and weakly continuous on $\mathcal{M} \cap \mathcal{L}$.*

Proof. From (2.4), $C^Q(T, K) \leq S_0$. Absence of arbitrage in the market implies that the market option prices satisfy the same condition. Therefore, $(C_M(T, K) - C^Q(T, K))^2 \leq S_0^2$ and, since w is a probability measure, $\|C_M - C^Q\|_w^2 \leq S_0^2$.

Let $\{Q_n\}_{n \geq 1} \subset \mathcal{M} \cap \mathcal{L}$ and $Q \in \mathcal{M} \cap \mathcal{L}$ be such that $Q_n \Rightarrow Q$. For all T, K ,

$$\begin{aligned} \lim_n C^{Q_n}(T, K) &= e^{-rT} \lim_n E^{Q_n}[(S_0 e^{rT+X_T} - K)^+] \\ &= e^{-rT} \lim_n E^{Q_n}[S_0 e^{rT+X_T} - K] + e^{-rT} \lim_n E^{Q_n}[(K - S_0 e^{rT+X_T})^+] \\ &= S_0 - K e^{-rT} + e^{-rT} E^Q[(K - S_0 e^{rT+X_T})^+] = C^Q(T, K). \end{aligned}$$

Therefore, by the dominated convergence theorem, $\|C_M - C^{Q_n}\|_w^2 \rightarrow \|C_M - C^Q\|_w^2$. \square

The calibration problem now takes the following form.

PROBLEM 2 (least squares calibration problem). *Given prices C_M of call options, find $Q^* \in \mathcal{M} \cap \mathcal{L}$ such that*

$$(3.4) \quad \|C_M - C^{Q^*}\|_w^2 = \inf_{Q \in \mathcal{M} \cap \mathcal{L}} \|C_M - C^Q\|_w^2.$$

In what follows, any such Q^* will be called a least squares solution and the set of all least squares solutions will be denoted by $\text{LSS}(C_M)$.

Several authors [2, 8] have used least squares formulations similar to (3.4) for calibrating parametric models without taking into account that the least squares calibration problem is ill-posed in several ways:

Lack of identification. Option prices are only available for a finite number of strikes (typically between 10 and 100) and knowing the prices of a finite number of options is not sufficient to reconstruct the Lévy process. This problem is discussed in detail in [14, 36].

Absence of solution. In some cases even the least squares problem may not admit a solution, as shown by the following (artificial) example.

Example 3.1. Suppose that $S_0 = 1$, there are no interest rates or dividends, and the (equally weighted) market data consist of the following two observations:

$$(3.5) \quad C_M(T = 1, K = 1) = 1 - e^{-\lambda} \quad \text{and} \quad C_M(T = 1, K = e^\lambda) = 0,$$

with some $\lambda > 0$. It is easy to see that these prices are, for example, compatible with the (martingale) asset price process $S_t = e^{\lambda t} 1_{t \leq \tau_1}$, where τ_1 is the time of the first jump of a Poisson process with intensity λ . We will show that if the market data are given by (3.5), the calibration problem (3.4) does not admit a solution.

Equation (2.4) implies that in every risk-neutral model Q , for fixed T , $C^Q(T, K)$ is a convex function of K and that $C^Q(T, K = 0) = 1$. The only convex function which satisfies this equality and passes through the market data points (3.5) is given by $C(T = 1, K) = (1 - K e^{-\lambda})^+$. Therefore, in every arbitrage-free model that is an exact solution of the calibration problem with market data (3.5), for every $K \geq 0$, $P[S_1 \leq K] = e^{-\lambda} 1_{K \leq e^\lambda}$. Since in an exponential Lévy model $P[S_1 > 0] = 1$, there is no risk-neutral exponential Lévy model for which $\|C_M - C^Q\|_w = 0$.

On the other hand, $\inf_{Q \in \mathcal{M} \cap \mathcal{L}} \|C_M - C^Q\|_w^2 = 0$. Indeed, let $\{N_t\}_{t \geq 0}$ be a Poisson process with intensity λ . Then for every n , the process

$$(3.6) \quad X_t^n := -nN_t + \lambda t(1 - e^{-n})$$

belongs to $\mathcal{M} \cap \mathcal{L}$ and

$$\lim_{n \rightarrow \infty} E[(e^{X_t^n} - K)^+] = \lim_{n \rightarrow \infty} \sum_{k=0}^{\infty} e^{-\lambda t} \frac{(\lambda t)^k}{k!} \left(e^{-nk + \lambda t(1 - e^{-n})} - K \right)^+ = (1 - K e^{-\lambda t})^+.$$

We have shown that $\inf_{Q \in \mathcal{M} \cap \mathcal{L}} \|C_M - C^Q\|^2 = 0$ and that for no Lévy process $Q \in \mathcal{M} \cap \mathcal{L}$, $\|C_M - C^Q\|^2 = 0$. Thus the calibration problem (3.4) does not admit a solution.

Lack of continuity of solutions with respect to market data. Market option prices are typically defined up to a bid-ask spread and the prices used for calibration may therefore be subject to perturbations of this order. If the solution of the calibration problem is not continuous with respect to market data, these small errors may dramatically alter the result of calibration, rendering it useless. In addition, in absence of continuity small daily changes in prices could lead to large variations of calibrated parameters and of quantities computed using these parameters, such as prices of exotic options.

When the calibration problem has more than one solution, care should be taken in defining continuity. In what follows, we will use the following definition [7, 20].

DEFINITION 3.2 (continuity with respect to data). *The solutions of a calibration problem are said to depend continuously on input data at the point C_M if for every sequence of data sets $\{C_M^n\}_{n \geq 0}$ such that $\|C_M^n - C_M\|_w \xrightarrow{n \rightarrow \infty} 0$; if, for every n , Q_n is a solution of the calibration problem with data C_M^n , then*

1. $\{Q_n\}_{n \geq 1}$ has a weakly convergent subsequence $\{Q_{n_m}\}_{m \geq 1}$.
2. The limit Q of every weakly convergent subsequence of $\{Q_n\}_{n \geq 1}$ is a solution of the calibration problem with data C_M .

If the solution of the calibration problem with the limiting data C_M is unique, this definition reduces to the standard definition of continuity, because in this case every subsequence of $\{Q_n\}$ has a further subsequence converging towards Q , which implies $Q_n \Rightarrow Q$.

Remark 3.1. Note that the above definition can accommodate the presence of random errors (“noise”) in the data. In this case the observational error can be described by a separate probability space $(\Omega_0, \mathcal{E}, p_0)$. The continuity property must then be interpreted as almost-sure continuity with respect to the law p_0 of the observational errors: for every (random) sequence $\{C_M^n\}_{n \geq 0}$ such that $\|C_M^n - C_M\|_w \xrightarrow{n \rightarrow \infty} 0$ almost surely, any sequence of solutions with data $\{C_M^n\}_{n \geq 0}$ must verify the properties of Definition 3.2 p_0 -almost surely.

It is easy to construct an example of market data leading to a least squares calibration problem (3.4) that does not satisfy the above definition.

Example 3.2. Assume $S_0 = 1$, no interest rates or dividends, and observations given by a single option price:

$$C_M^n(T = 1, K = 1) = E[(e^{X_1^n} - 1)^+] \quad \text{for } n \geq 1 \quad \text{and} \quad C_M(T = 1, K = 1) = 1 - e^{-\lambda},$$

where X_t^n is defined by (3.6) and $\lambda > 0$. Then $\|C_M^n - C_M\|_w \xrightarrow{n \rightarrow \infty} 0$ and X_t^n is a solution for data C_M^n , but the sequence $\{X_t^n\}$ has no convergent subsequence (cf. Corollary VII.3.6 in [27]).

In addition to these theoretical obstacles, even if a solution exists, it may be difficult to compute numerically since, as shown in [14, 36], the pricing error $\|C_M - C^Q\|^2$ is typically nonconvex and can have many local minima, preventing a gradient-based minimization algorithm from finding the solution.

4. Relative entropy as a selection criterion. When constraints given by option prices do not determine the exponential Lévy model completely, additional information may be introduced into the problem by specifying a *prior model*: we start from a reference Lévy process P and look for the solution of the problem (3.4) that has the smallest relative entropy with respect to P . For two probabilities P and Q on the same measurable space (Ω, \mathcal{F}) , the relative entropy of Q with respect to P

is defined by

$$(4.1) \quad I(Q|P) = \begin{cases} E^P \left[\frac{dQ}{dP} \log \frac{dQ}{dP} \right] & \text{if } Q \ll P, \\ \infty & \text{otherwise,} \end{cases}$$

where by convention $x \log x = 0$ when $x = 0$. We define $I_T(Q|P) := I(Q|_{\mathcal{F}_T}|P|_{\mathcal{F}_T})$.

PROBLEM 3 (minimum entropy least squares calibration problem). *Given prices C_M of call options and a prior Lévy process P , find a least squares solution $Q^* \in \text{LSS}(C_M)$, such that*

$$(4.2) \quad I(Q^*|P) = \inf_{Q \in \text{LSS}(C_M)} I(Q|P).$$

In what follows, any such Q^* will be called a minimum entropy least squares solution (MELSS) and the set of all such solutions will be denoted by $\text{MELSS}(C_M)$.

P reflects a priori knowledge about the nature of possible trajectories of the underlying asset and their probabilities of occurrence. A natural choice of prior, ensuring absence of arbitrage in the calibrated model, is an exponential Lévy model estimated from the time series of returns. Whether this choice is adopted or not does not affect our discussion below. Other possible ways to choose the prior model in practice are discussed in [14], which also gives an empirical analysis of the effect of the choice of prior on the solution of the calibration problem.

The choice of relative entropy as a method for selection of solutions of the calibration problem is driven by the following considerations:

- Relative entropy can be interpreted as a (pseudo-)distance to the prior P : it is convex, nonnegative functional of Q for fixed P , and equal to zero if and only if $\frac{dQ}{dP} = 1$ P -a.s. To see this, observe that

$$E^P \left[\frac{dQ}{dP} \log \frac{dQ}{dP} \right] = E^P \left[\frac{dQ}{dP} \log \frac{dQ}{dP} - \frac{dQ}{dP} + 1 \right],$$

and that $z \log z - z + 1$ is a convex nonnegative function of z , equal to zero if and only if $z = 1$.

- Relative entropy for Lévy processes is easily expressed in terms of their characteristic triplets (see Theorem A.1).
- Relative entropy has an information-theoretic interpretation and has been repeatedly used for model selection in finance (see section 1).

Using relative entropy for the selection of solutions removes, to some extent, the identification problem of least squares calibration. Whereas in the least squares case this was an important nuisance, now, if two measures reproduce market option prices with the same precision and have the same entropy relative to the prior, this means that both measures are compatible with all the available information. Knowledge of many such probability measures instead of one may be seen as an advantage, because it allows us to estimate model risk and provide confidence intervals for the prices of exotic options [12]. However, the calibration problem (4.2) remains ill-posed: since the minimization of entropy is done over the results of least squares calibration, problem (4.2) may only admit a solution if problem (3.4) does. Also, $\text{LSS}(C_M)$ is not necessarily a compact set, so even if it is nonempty, (4.2) may not have a solution. Other undesirable properties such as absence of continuity and numerical instability are also inherited from the least squares approach.

The MELSS does not always exist, but if the prior is chosen correctly such that (3.4) admits a solution with finite relative entropy with respect to the prior, then MELSSs will also exist.

LEMMA 4.1. *Let $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$ for some $B > 0$ and assume problem (3.4) admits a solution Q^+ with $I(Q^+|P) = C < \infty$. Then problem (4.2) admits a solution.*

Proof. Under the condition of the lemma, it is clear that the solution Q^* of problem (4.2), if it exists, satisfies $I(Q^*|P) \leq C$. This entails that $Q^* \ll P$, which means by Theorem IV.4.39 in [27] that $Q^* \in \mathcal{L}_B^+$. Therefore, Q^* belongs to the set

$$(4.3) \quad \mathcal{L}_B^+ \cap \{Q \in \mathcal{M} \cap \mathcal{L} : \|C^Q - C_M\| = \|C^{Q^+} - C_M\|\} \cap \{Q \in \mathcal{L} : I(Q|P) \leq C\}.$$

Lemma A.2 and the Prohorov's theorem entail that the level set $\{Q \in \mathcal{L} : I(Q|P) \leq C\}$ is relatively weakly compact. On the other hand, by Corollary A.4, $I(Q|P)$ is weakly lower semicontinuous with respect to Q for fixed P . Therefore, the set $\{Q \in \mathcal{P}(\Omega) : I(Q|P) \leq C\}$ is weakly closed, and since by Lemma 2.1 $\mathcal{M} \cap \mathcal{L}_B^+$ is also weakly closed, the set $\mathcal{M} \cap \mathcal{L}_B^+ \cap \{Q \in \mathcal{L} : I(Q|P) \leq C\}$ is weakly compact. Lemma 3.1 then implies that the set (4.3) is also weakly compact. Since $I(Q|P)$ is weakly lower semicontinuous, it reaches its minimum on this set. \square

Remark 4.1. It is essential for our analysis that the model has discontinuous trajectories, i.e., the prior P corresponds to a process with jumps, not a diffusion process. If P corresponds to the law of a Markovian diffusion model, then the set of processes which have both the martingale property and finite entropy with respect to P is reduced to a single element and the solution to 4.2 is trivial (this follows, e.g., from Theorem IV.4.39 in [27]).

5. Regularization using relative entropy. As observed in [14] and in section 4, problem (4.2) is ill-posed and hard to solve numerically. In particular its solutions, when they exist, may not be stable with respect to perturbations of market data. If we do not know the prices C_M exactly but only dispose of observations C_M^δ with $\|C_M^\delta - C_M\|_w \leq \delta$ and want to construct an approximation to $\text{MELSS}(C_M)$, it is not a good idea to solve problem (4.2) with the noisy data C_M^δ because $\text{MELSS}(C_M^\delta)$ may be very different from $\text{MELSS}(C_M)$. We therefore need to regularize the problem (4.2), that is, construct a family of continuous “regularization operators” $\{R_\alpha\}_{\alpha>0}$, where α is the regularization parameter such that $R_\alpha(C_M^\delta)$ converges to an MELSS as the noise level δ tends to zero if an appropriate parameter choice rule $\delta \mapsto \alpha(\delta)$ is used [20]. The approximation to $\text{MELSS}(C_M)$ using the noisy data C_M^δ is then given by $R_\alpha(C_M^\delta)$ with an appropriate choice of α .

Following a classical approach to regularization of ill-posed problems [20, 4], we regularize (4.2) by using the relative entropy as a penalization term:

$$(5.1) \quad J_\alpha(Q) = \|C_M^\delta - C^Q\|_w^2 + \alpha I(Q|P),$$

where α is the regularization parameter. We then solve the following optimization problem.

PROBLEM 4 (regularized calibration problem). *Given prices C_M of call options, a prior Lévy process P , and a regularization parameter $\alpha > 0$, find $Q^* \in \mathcal{M} \cap \mathcal{L}$ such that*

$$(5.2) \quad J_\alpha(Q^*) = \inf_{Q \in \mathcal{M} \cap \mathcal{L}} J_\alpha(Q).$$

Problem (5.2) can be thought of in two ways:

- If the MELSS with the true data C_M exists, (5.2) allows us to construct a stable approximation of this solution using the noisy data.
- If the $\text{MELSS}(C_M) = \emptyset$, either because the set of least squares solutions is empty or because the least squares solutions are incompatible with the prior, the regularized problem (5.2) allows us to achieve, in a stable manner, a trade-off between matching the constraints and the prior information.

In the rest of this section we study the regularized calibration problem. Under our standing hypothesis that the prior Lévy process has jumps bounded from above and corresponds to an arbitrage-free market ($P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$), we show that the regularized calibration problem always admits a solution that depends continuously on the market data. In addition, we give a sufficient condition on the prior P for the solution to be an *equivalent* martingale measure and show how the regularization parameter α must be chosen depending on the noise level δ if the regularized solutions are to converge to the solutions of the minimum entropy least squares calibration problem (4.2).

5.1. Existence of solutions. The following result shows that, unlike the exact or the least squares formulations, the regularized inverse problem always admits a solution.

THEOREM 5.1. *Let $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$ for some $B > 0$. Then the calibration problem (5.2) has a solution $Q^* \in \mathcal{M} \cap \mathcal{L}_B^+$.*

Proof. By Lemma A.5, there exists $Q^0 \in \mathcal{M} \cap \mathcal{L}$ with $I(Q^0|P) < \infty$. The solution, if it exists, must belong to the level set $L_{J_\alpha(Q^0)} := \{Q \in \mathcal{L} : I(Q|P) \leq J_\alpha(Q^0)\}$. Since $J_\alpha(Q^0) = \|C_M - C^{Q^0}\|_w^2 + I(Q^0|P) < \infty$, by Lemma A.2 $L_{J_\alpha(Q^0)}$ is tight and, by Prohorov's theorem, weakly relatively compact. Corollary A.4 entails that $I(Q|P)$ is weakly lower semicontinuous with respect to Q . Therefore, $\{Q \in \mathcal{P}(\Omega) : I(Q|P) \leq J_\alpha(Q^0)\}$ is weakly closed, and since by Lemma 2.1 $\mathcal{M} \cap \mathcal{L}_B^+$ is weakly closed, $\mathcal{M} \cap \mathcal{L}_B^+ \cap L_{J_\alpha(Q^0)}$ is weakly compact. Moreover, by Lemma 3.1 the squared pricing error is weakly continuous, which entails that $J_\alpha(Q)$ is weakly lower semicontinuous. Therefore, $J_\alpha(Q)$ achieves its minimum value on $\mathcal{M} \cap \mathcal{L}_B^+ \cap L_{J_\alpha(Q^0)}$, which proves the theorem. \square

Since $P \in \mathcal{L}_B^+$ (i.e., with jumps of X bounded from above P -a.s.), solutions Q are also in \mathcal{L}_B^+ . This may seem a limitation if the data is generated by a Lévy process with jumps unbounded from above. This case is unlikely in financial applications; the form of Lévy densities found empirically in [14] gives little evidence for large upward jumps. Even in the theoretical case where the observed option prices are generated by an exponential-Lévy model with jumps unbounded from above, the localization estimates in [15, Proposition 4.2.] show that we can reproduce such prices with a Lévy process in \mathcal{L}_B^+ by choosing B large enough.

Since every solution Q^* of the regularized calibration problem (5.2) has finite relative entropy with respect to the prior P , necessarily $Q^* \ll P$. However, Q^* need not in general be equivalent to the prior. When the prior corresponds to the “objective” probability measure, absence of arbitrage is guaranteed if options are priced using an *equivalent* martingale measure [25]. The following theorem gives a sufficient condition for this equivalence.

THEOREM 5.2. *Let $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$ and assume the characteristic function Φ_T^P of P satisfies*

$$(5.3) \quad \int_{-\infty}^{\infty} |\Phi_T^P(u)| du < \infty$$

for some $T < T_0$, where T_0 is the shortest maturity, present in the market data. Then every solution Q^* of the calibration problem (5.2) satisfies $Q^* \sim P$.

Remark 5.1. Condition (5.3) implies that the prior Lévy process has a continuous density at time T and all subsequent times. Two important examples of processes satisfying the condition (5.3) for all T are

- processes with nonzero Gaussian component ($A > 0$).
- processes with stablelike behavior of small jumps, that is, processes whose Lévy measure satisfies

$$(5.4) \quad \exists \beta \in (0, 2), \quad \liminf_{\varepsilon \downarrow 0} \varepsilon^{-\beta} \int_{-\varepsilon}^{\varepsilon} |x|^2 \nu(dx) > 0.$$

For a proof, see [34, Proposition 28.3]. This class includes tempered stable processes [13] with $\alpha_+ > 0$ and/or $\alpha_- > 0$.

To prove Theorem 5.2 we will use the following lemma.

LEMMA 5.3. *Let $P \in \mathcal{M} \cap \mathcal{L}_B^+$ with characteristic triplet (A, ν, γ) and characteristic exponent ψ . There exists $C < \infty$ such that*

$$\left| \frac{\psi(v-i)}{(v-i)v} \right| \leq C \quad \forall v \in \mathbb{R}.$$

Proof. From the Lévy–Khinchin formula and (2.3),

$$(5.5) \quad \psi(v-i) = -\frac{1}{2}Av(v-i) + \int_{-\infty}^{\infty} (e^{i(v-i)x} + iv - e^x - ive^x)\nu(dx).$$

Observe first that

$$e^{i(v-i)x} + iv - e^x - ive^x = iv(xe^x + 1 - e^x) + \frac{\theta v^2 x^2 e^x}{2} \quad \text{for some } \theta \text{ with } |\theta| \leq 1.$$

Therefore, for all v with $|v| \geq 2$,

$$(5.6) \quad \left| \frac{e^{i(v-i)x} + iv - e^x - ive^x}{(v-i)v} \right| \leq xe^x + 1 - e^x + x^2 e^x.$$

On the other hand,

$$\begin{aligned} \frac{e^{i(v-i)x} + iv - e^x - ive^x}{(v-i)v} &= \frac{ie^x(e^{ivx} - 1)}{v} - \frac{i(e^{i(v-i)x} - 1)}{v-i} \\ &= -xe^x - \frac{ivx^2}{2}e^{\theta_1 ivx} + x + \frac{i(v-i)x^2}{2}e^{\theta_2 i(v-i)x} \end{aligned}$$

with some $\theta_1, \theta_2 \in [0, 1]$. Therefore, for all v with $|v| \leq 2$,

$$(5.7) \quad \left| \frac{e^{i(v-i)x} + iv - e^x - ive^x}{(v-i)v} \right| \leq x(1 - e^x) + \frac{x^2}{2}(v + \sqrt{1 + v^2}e^x) \leq x(1 - e^x) + x^2(1 + 2e^x).$$

Since the support of ν is bounded from above, the right-hand sides of (5.6) and (5.7) are ν -integrable and the proof of the lemma is completed. \square

Proof of Theorem 5.2. Let Q^* be a solution of (5.2) with prior P . By Lemma A.5, there exists $Q^0 \in \mathcal{M} \cap \mathcal{L}$ such that $Q^0 \sim P$. Denote the characteristic triplet of Q^* by (A, ν^*, γ^*) and that of Q^0 by (A, ν^0, γ^0) .

Let Q_x be a Lévy process with characteristic triplet $(A, x\nu^0 + (1-x)\nu^*, x\gamma^0 + (1-x)\gamma^*)$. From the linearity of the martingale condition (2.3), it follows that for all $x \in [0, 1]$, $Q_x \in \mathcal{M} \cap \mathcal{L}$. Since Q^* realizes the minimum of $J_\alpha(Q)$, necessarily $J_\alpha(Q_x) - J_\alpha(Q^*) \geq 0$ for all $x \in [0, 1]$. Our strategy for proving the theorem is first to show that $\frac{\|C_M - C^{Q_x}\|^2 - \|C_M - C^{Q^*}\|^2}{x}$ is bounded as $x \rightarrow 0$ and then to show that if $\frac{I(Q_x|P) - I(Q^*|P)}{x}$ is bounded from below as $x \rightarrow 0$, necessarily $Q^* \sim P$.

The first step is to prove that the characteristic function Φ^* of Q^* satisfies the condition (5.3) for some $T < T_0$. If $A > 0$, this is trivial. Assume that $A = 0$. In this case, $|\Phi_T^*(u)| = \exp(T \int_{-\infty}^{\infty} (\cos(ux) - 1)\nu^*(dx))$. Denote $\frac{d\nu^*}{d\nu^P} := \phi^*$. Since $Q^* \ll P$, by Theorem IV.4.39 in [27], $\int_{-\infty}^{\infty} (\sqrt{\phi^*(x)} - 1)^2 \nu^P(dx) \leq K < \infty$ for some constant K . Therefore, there exists another constant $C > 0$ such that

$$\int_{\{\phi^*(x) > C\}} (1 - \cos(ux)) |\phi^* - 1| \nu^P(dx) < C$$

uniformly on u . For all $r > 0$,

$$\begin{aligned} \int_{-\infty}^{\infty} (1 - \cos(ux)) |\phi^* - 1| \nu^P(dx) &\leq C + \int_{\{\phi^*(x) \leq C\}} (1 - \cos(ux)) |\phi^* - 1| \nu^P(dx) \\ &\leq C + \frac{r}{2} \int_{\{\phi^*(x) \leq C\}} (1 - \cos(ux))^2 \nu^P(dx) + \frac{1}{2r} \int_{\{\phi^*(x) \leq C\}} (\phi^* - 1)^2 \nu^P(dx) \\ &\leq C + r \int_{-\infty}^{\infty} (1 - \cos(ux)) \nu^P(dx) + \frac{K(\sqrt{C} + 1)^2}{2r}. \end{aligned}$$

This implies

$$\int_{-\infty}^{\infty} (\cos(ux) - 1) \nu^*(dx) \leq (1+r) \int_{-\infty}^{\infty} (\cos(ux) - 1) \nu^P(dx) + C + \frac{K(\sqrt{C} + 1)^2}{2r}$$

for all $r > 0$. Therefore, if the characteristic function of P satisfies the condition (5.3) for some T , the characteristic function of Q^* will satisfy it for every $T' > T$.

Since $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$, $Q_x \in \mathcal{M} \cap \mathcal{L}_B^+$ for all $x \in [0, 1]$. Therefore, condition (11.15) in [13] is satisfied and option prices can be computed using equation (11.20) of [13]:²

$$\begin{aligned} C^{Q_x}(T, K) &= (1 - Ke^{-rT})^+ \\ &+ \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-iv \log K + ivrT} \frac{\exp(T(1-x)\psi^*(v-i) + Tx\psi^0(v-i)) - 1}{iv(1+iv)} dv, \end{aligned}$$

where ψ^0 and ψ^* denote the characteristic exponents of Q_0 and Q^* . It follows that

$$\begin{aligned} \frac{C^{Q_x}(T, K) - C^{Q^*}(T, K)}{x} &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-iv \log K + ivrT} \frac{e^{T(1-x)\psi^*(v-i) + Tx\psi^0(v-i)} - e^{T\psi^*(v-i)}}{iv(1+iv)x} dv. \end{aligned}$$

²This method for option pricing by Fourier transform is originally due to Carr and Madan [10].

Since $\Re\psi^0(v-i) \leq 0$ and $\Re\psi^*(v-i) \leq 0$ for all $v \in \mathbb{R}$, Lemma 5.3 implies

$$\begin{aligned} & \left| e^{-iv \log K + ivrT} \frac{e^{T(1-x)\psi^*(v-i) + Tx\psi^0(v-i)} - e^{T\psi^*(v-i)}}{iv(1+iv)x} \right| \\ & \leq T \frac{|e^{T(1-x)\psi^*(v-i)}| |\psi^0(v-i) - \psi^*(v-i)|}{|v(1+iv)|} \leq T |e^{T(1-x)\psi^*(v-i)}| C' \end{aligned}$$

for some constant C' . From the dominated convergence theorem and since Q^* satisfies (5.3), $\frac{\partial C^{Q_x}(T, K)}{\partial x}|_{x=0}$ exists and is bounded uniformly on T and K in the market data set. This in turn means that $\frac{\|C_M - C^{Q_x}\|^2 - \|C_M - C^{Q^*}\|^2}{x}$ is bounded as $x \rightarrow 0$. To complete the proof, it remains to show that if $\frac{I(Q_x|P) - I(Q^*|P)}{x}$ is bounded from below as $x \rightarrow 0$, necessarily $Q^* \sim P$. Using the convexity (with respect to ν^Q and γ^Q) of the two terms in the expression (A.1) for relative entropy, we have

$$\begin{aligned} & \frac{I(Q_x|P) - I(Q^*|P)}{x} \\ &= \frac{T_\infty}{2Ax} \left\{ x\gamma^0 + (1-x)\gamma^* - \gamma^P - \int_{|z| \leq 1} z(x\nu^0 + (1-x)\nu^* - \nu^P)(dz) \right\}^2 \mathbf{1}_{A \neq 0} \\ & \quad - \frac{T_\infty}{2Ax} \left\{ \gamma^* - \gamma^P - \int_{|z| \leq 1} z(\nu^* - \nu^P)(dz) \right\}^2 \mathbf{1}_{A \neq 0} \\ & \quad + \frac{T_\infty}{x} \int_{-\infty}^{\infty} \{(x\phi^0 + (1-x)\phi^*) \log(x\phi^0 + (1-x)\phi^*) - x\phi^0 - (1-x)\phi^* + 1\} \nu^P(dz) \\ & \quad - \frac{T_\infty}{x} \int_{-\infty}^{\infty} \{\phi^* \log(\phi^*) - \phi^* + 1\} \nu^P(dz) \\ & \leq \frac{T_\infty}{2A} \left\{ \gamma^0 - \gamma^P - \int_{|z| \leq 1} z(\nu^0 - \nu^P)(dz) \right\}^2 \mathbf{1}_{A \neq 0} \\ & \quad - \frac{T_\infty}{2A} \left\{ \gamma^* - \gamma^P - \int_{|z| \leq 1} z(\nu^* - \nu^P)(dz) \right\}^2 \mathbf{1}_{A \neq 0} \\ & \quad + T_\infty \int_{\{\phi^* > 0\}} \{\phi^0 \log(\phi^0) - \phi^0 + 1\} \nu^P(dz) - T_\infty \int_{\{\phi^* > 0\}} \{\phi^* \log(\phi^*) - \phi^* + 1\} \nu^P(dz) \\ & \quad + T_\infty \int_{\{\phi^* = 0\}} \{\phi^0 \log(x\phi^0) - \phi^0\} \nu^P(dz) \leq I(Q_0|P) + T_\infty \int_{\{\phi^* = 0\}} (\phi_0 \log x - 1) \nu^P(dz). \end{aligned}$$

Since $J_\alpha(Q_x) - J_\alpha(Q^*) \geq 0$, this expression must be bounded from below. Therefore, because $\phi_0 > 0$, necessarily $\nu^P(\{\phi^* = 0\}) = 0$ and Theorem IV.4.39 in [27] entails that $P \ll Q^*$. \square

5.2. Continuity of solutions with respect to data.

THEOREM 5.4 (continuity of solutions with respect to data). *Let $\{C_M^n\}_{n \geq 1}$ and C_M be data sets of option prices such that*

$$\|C_M^n - C_M\|_w \xrightarrow{n \rightarrow \infty} 0.$$

Let $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$, $\alpha > 0$, and for each n let Q_n be a solution of the calibration problem (5.2) with data C_M^n , prior Lévy process P , and regularization parameter α .

Then $\{Q_n\}_{n \geq 1}$ has a subsequence converging weakly to $Q^* \in \mathcal{M} \cap \mathcal{L}_B^+$, and the limit of every converging subsequence of $\{Q_n\}_{n \geq 1}$ is a solution of calibration problem (5.2) with data C_M , prior P , and regularization parameter α .

Proof. By Lemma A.5, there exists $Q^0 \in \mathcal{M} \cap \mathcal{L}$ with $I(Q^0|P) < \infty$. Since, by Lemma 3.1, $\|C^{Q^0} - C_M^n\|^2 \leq S_0^2$ for all n , $\alpha I(Q_n|P) \leq S_0^2 + \alpha I(Q^0|P)$ for all n . Therefore, by Lemmas 2.1 and A.2 and Prohorov's theorem, $\{Q_n\}_{n \geq 1}$ is weakly relatively compact. Together with Lemma 2.1 this proves the first part of the theorem. \square

Choose any subsequence of $\{Q_n\}_{n \geq 1}$ converging weakly to $Q^* \in \mathcal{M} \cap \mathcal{L}_B^+$. To simplify notation, this subsequence is denoted again by $\{Q_n\}_{n \geq 1}$. The triangle inequality and Lemma 3.1 imply that

$$(5.8) \quad \|C^{Q_n} - C_M^n\|^2 \xrightarrow{n \rightarrow \infty} \|C^{Q^*} - C_M\|^2.$$

Since, by Lemma A.3, the relative entropy functional is weakly lower semicontinuous with respect to Q , for every $Q \in \mathcal{M} \cap \mathcal{L}_B^+$,

$$\begin{aligned} \|C^{Q^*} - C_M\|^2 + \alpha I(Q^*|P) &\leq \liminf_n \{\|C^{Q_n} - C_M^n\|^2 + \alpha I(Q_n|P)\} \\ &\leq \liminf_n \{\|C^Q - C_M^n\|^2 + \alpha I(Q|P)\} \\ &= \lim_n \|C^Q - C_M^n\|^2 + \alpha I(Q|P) \\ &= \|C^Q - C_M\|^2 + \alpha I(Q|P), \end{aligned}$$

where the second inequality follows from the fact that Q_n is the solution of the calibration problem with data C_M^n and the last line follows from the triangle inequality.

5.3. Convergence to MELSSs. The convergence analysis of regularization methods for inverse problems usually involves the study of the solution of the regularized problem as the noise level δ vanishes, the regularization parameter being chosen as a function $\alpha(\delta)$ of the noise level using some parameter choice rule. The following result gives conditions on the parameter choice rule $\delta \mapsto \alpha(\delta)$ under which the solutions of the regularized problem (5.2) converge to MELSSs defined by (4.2).

THEOREM 5.5. *Let $\{C_M^\delta\}$ be a family of data sets of option prices such that $\|C_M - C_M^\delta\| \leq \delta$, let $P \in \mathcal{L}_{NA} \cap \mathcal{L}_B^+$, and assume there exists a solution Q of problem (3.4) with data C_M (a least squares solution) such that $I(Q|P) < \infty$.*

In the case where the constraints are attainable, i.e., $\|C^Q - C_M\| = 0$, let $\alpha(\delta)$ be such that $\alpha(\delta) \rightarrow 0$ and $\frac{\delta^2}{\alpha(\delta)} \rightarrow 0$ as $\delta \rightarrow 0$. Otherwise, let $\alpha(\delta)$ be such that $\alpha(\delta) \rightarrow 0$ and $\frac{\delta}{\alpha(\delta)} \rightarrow 0$ as $\delta \rightarrow 0$.

Then every sequence $\{Q^{\delta_k}\}$, where $\delta_k \rightarrow 0$ and Q^{δ_k} is a solution of problem (5.2) with data $C_M^{\delta_k}$, prior P , and regularization parameter $\alpha(\delta_k)$, has a weakly convergent subsequence. The limit of every convergent subsequence is a solution of problem (4.2) with data C_M and prior P . If the MELSS is unique ($\text{MELSS}(C_M) = \{Q^+\}$), then

$$Q^\delta \xrightarrow{\delta \rightarrow 0} Q^+.$$

Proof. By Lemma 4.1, there exists at least one MELSS with data C_M and prior P , with finite relative entropy with respect to the prior. Let $Q^+ \in \text{MELSS}(C_M)$. Since Q^{δ_k} is the solution of the regularized problem, for every k ,

$$\|C^{Q^{\delta_k}} - C_M^{\delta_k}\|^2 + \alpha(\delta_k)I(Q^{\delta_k}|P) \leq \|C^{Q^+} - C_M^{\delta_k}\|^2 + \alpha(\delta_k)I(Q^+|P).$$

Using the fact that for every $r > 0$ and for every $x, y \in \mathbb{R}$,

$$(1-r)x^2 + (1-1/r)y^2 \leq (x+y)^2 \leq (1+r)x^2 + (1+1/r)y^2,$$

we obtain that

$$(5.9) \quad (1-r)\|C^{Q^{\delta_k}} - C_M\|^2 + \alpha(\delta_k)I(Q^{\delta_k}|P) \\ \leq (1+r)\|C^{Q^+} - C_M\|^2 + \frac{2\delta_k^2}{r} + \alpha(\delta_k)I(Q^+|P),$$

and since $Q^+ \in \text{LSS}(C_M)$, this implies for all $r \in (0, 1)$ that

$$(5.10) \quad \alpha(\delta_k)I(Q^{\delta_k}|P) \leq 2r\|C^{Q^+} - C_M\|^2 + \frac{2\delta_k^2}{r} + \alpha(\delta_k)I(Q^+|P).$$

If the constraints are met exactly, $\|C^{Q^+} - C_M\| = 0$, and with the choice $r = 1/2$, the above expression yields

$$I(Q^{\delta_k}|P) \leq \frac{4\delta_k^2}{\alpha(\delta_k)} + I(Q^+|P).$$

Since, by the theorem's statement, in the case of exact constraints $\frac{\delta_k^2}{\alpha(\delta_k)} \rightarrow 0$, this implies

$$(5.11) \quad \limsup_k \{I(Q^{\delta_k}|P)\} \leq I(Q^+|P).$$

If $\|C^{Q^+} - C_M\| > 0$ (misspecified model), then the right-hand side of (5.10) achieves its maximum when $r = \delta_k\|C^{Q^+} - C_M\|^{-1}$, in which case we obtain

$$I(Q^{\delta_k}|P) \leq \frac{4\delta_k}{\alpha(\delta_k)}\|C^{Q^+} - C_M\| + I(Q^+|P).$$

Since in the case of approximate constraints $\frac{\delta_k}{\alpha(\delta_k)} \rightarrow 0$, we obtain (5.11) once again.

Inequality (5.11) implies in particular that $I(Q^{\delta_k}|P)$ is uniformly bounded, which proves, by Lemmas A.2 and 2.1, that $\{Q^{\delta_k}\}$ is relatively weakly compact in $\mathcal{M} \cap \mathcal{L}_B^+$.

Choose a subsequence of $\{Q^{\delta_k}\}$ converging weakly to $Q^* \in \mathcal{M} \cap \mathcal{L}_B^+$. To simplify notation, this subsequence is denoted again by $\{Q^{\delta_k}\}_{k \geq 1}$. Substituting $r = \delta$ into (5.9) and making k tend to infinity shows that

$$\limsup_k \|C^{Q^{\delta_k}} - C_M\|^2 \leq \|C^{Q^+} - C_M\|^2.$$

Together with Lemma 3.1 this implies that

$$\|C^{Q^*} - C_M\|^2 \leq \|C^{Q^+} - C_M\|^2;$$

hence Q^* is a least squares solution. By weak lower semicontinuity of I (cf. Lemma A.3) and using (5.11),

$$I(Q^*|P) \leq \liminf_k I(Q^{\delta_k}|P) \leq \limsup_k I(Q^{\delta_k}|P) \leq I(Q^+|P),$$

which means that $Q^* \in \text{MELSS}(C_M)$. The last assertion of the theorem follows from the fact that in this case every subsequence of $\{Q^{\delta_k}\}$ has a further subsequence converging toward Q^+ . \square

Remark 5.2 (random errors). In line with Remark 3.1, it is irrelevant whether the noise in the data is “deterministic” or “random,” as long the error level δ is interpreted as a worst-case error level, i.e., an almost-sure bound on the error:

$$(5.12) \quad \mathbb{P}_0(\|C_M^\delta - C_M\| \leq \delta) = 1.$$

In this case, Theorem 5.5 holds for random errors, convergence being interpreted as almost-sure convergence with respect to the law \mathbb{P}_0 of the errors.

6. Stability with respect to the prior. If we choose a prior Lévy process P with a finite number of jump sizes (sometimes called *simple* Lévy processes),

$$(6.1) \quad \nu^P = \sum_{k=0}^{M-1} p_k \delta_{\{x_k\}}(dx),$$

then the solution Q satisfies $Q \ll P$ by Theorem IV.4.39 in [27]. Thus the corresponding Lévy measure ν^Q satisfies $\nu^Q \ll \nu^P$ and is of the form

$$(6.2) \quad \nu^Q = \sum_{k=0}^{M-1} q_k \delta_{\{x_k\}}(dx).$$

The calibration problem (5.2) is then a finite-dimensional optimization problem and can be solved using a numerical optimization algorithm [14]. The advantage of this method is that we are simply solving (5.2) with a specific choice of prior, so all results of section 5 hold. Numerical methods for solving this problem are discussed in the companion paper [14]. Here we will complement these results by a theorem showing that the solution of a calibration problem with any prior can be approximated (in the weak sense) by a sequence of solutions of calibration problems with simple Lévy processes as priors. We start by showing that every Lévy process can be approximated by simple Lévy processes of the form (6.1).

LEMMA 6.1. *Let P be a Lévy process with characteristic triplet (A, ν, γ) with respect to a continuous truncation function h ; for every n , let P_n be a Lévy process with characteristic triplet (A, ν_n, γ) (with respect to h), where*

$$\nu_n := \sum_{k=1}^{2n} \delta_{\{x_k\}}(dx) \frac{\mu([x_k - 1/\sqrt{n}, x_k + 1/\sqrt{n}])}{1 \wedge x_k^2},$$

$x_k := (2(k - n) - 1)/\sqrt{n}$, and μ is a (positive and finite) measure on \mathbb{R} , defined by $\mu(B) := \int_B (1 \wedge x^2) \nu(dx)$ for all $B \in \mathcal{B}(\mathbb{R})$. Then $P_n \Rightarrow P$.

Proof. For a function $f \in C_b(\mathbb{R})$, define

$$f_n(x) := \begin{cases} 0, & x \geq 2\sqrt{n}, \\ 0, & x < -2\sqrt{n}, \\ f(x_i), & x \in [x_i - 1/\sqrt{n}, x_i + 1/\sqrt{n}] \quad \text{with } 1 \leq i \leq 2n. \end{cases}$$

Then $\int (1 \wedge x^2) f(x) \nu_n(dx) = \int f_n(x) \mu(dx)$. Since $f(x)$ is continuous, $f_n(x) \xrightarrow{n \rightarrow \infty} f(x)$ for all x and since f is bounded, the dominated convergence theorem implies

$$(6.3) \quad \lim_n \int (1 \wedge x^2) f(x) \nu_n(dx) = \lim_n \int f_n(x) \mu(dx) = \int (1 \wedge x^2) f(x) \nu(dx).$$

With $f(x) \equiv \frac{h^2(x)}{1 \wedge x^2}$ the above yields

$$\int h^2(x) \nu_n(dx) \xrightarrow{n \rightarrow \infty} \int h^2(x) \nu(dx).$$

On the other hand, for every $g \in C_b(\mathbb{R})$ such that $g(x) \equiv 0$ on a neighborhood of 0, $f(x) := \frac{g(x)}{1 \wedge x^2}$ belongs to $C_b(\mathbb{R})$. Therefore, from (6.3), $\lim_n \int g(x) \nu_n(dx) = \int g(x) \nu(dx)$ and by Corollary VII.3.6 in [27], $P_n \Rightarrow P$. \square

To compute numerically the solution of the calibration problem (5.2) with a given prior P , we can construct, using Lemma 6.1, an approximating sequence $\{P_n\}$ of simple Lévy processes such that $P_n \Rightarrow P$. Problem (5.2) with P replaced by P_n is then a finite-dimensional optimization problem that can be solved. The resulting sequence $\{Q_n\}$ of solutions will converge, as shown in the following theorem, to a solution of the calibration problem with prior P .

THEOREM 6.2. *Let $P, \{P_n\}_{n \geq 1} \subset \mathcal{L}_{NA} \cap \mathcal{L}_B^+$ such that $P_n \Rightarrow P$. Let $\alpha > 0$, let C_M be a data set of option prices, and for each $n \geq 1$ let Q_n be a solution of the calibration problem (5.2) with prior P_n , regularization parameter α , and data C_M . Denote the characteristic triplet (with respect to a continuous truncation function h) of P_n by $(A_n, \nu_n^P, \gamma_n^P)$ and that of P by (A, ν^P, γ^P) . If $A_n \rightarrow A > 0$, then the sequence $\{Q_n\}_{n \geq 1}$ has a weakly convergent subsequence and the limit of every weakly convergent subsequence of $\{Q_n\}_{n \geq 1}$ is a solution of the calibration problem (5.2) with prior P .*

Proof. By Lemma A.5, there exists $C < \infty$ such that for every n one can find $\tilde{Q}_n \in \mathcal{M} \cap \mathcal{L}$ with $I(\tilde{Q}_n | P_n) \leq C$. Since $\|C^{\tilde{Q}_n} - C_M\|_w^2 \leq S_0^2$ for every n and Q_n is the solution of the calibration problem, $I(Q_n | P_n) \leq S_0^2/\alpha + C < \infty$ for every n . Therefore, by Lemma A.2, $\{Q_n\}$ is tight and, by Prohorov's theorem and Lemma 2.1, weakly relatively compact in $\mathcal{M} \cap \mathcal{L}_B^+$. Choose a subsequence of $\{Q_n\}$ converging weakly to $Q \in \mathcal{M} \cap \mathcal{L}_B^+$. To simplify notation, this subsequence is also denoted by $\{Q_n\}_{n \geq 1}$. It remains to show that Q is indeed a solution of (5.2). We can parameterize the characteristic triplet of any $Q^\phi \in \mathcal{M} \cap \mathcal{L}$ with $I(Q | P) < \infty$ as

$$\left(A, \phi \nu^P, \gamma^\phi := -\frac{A}{2} - \int_{-\infty}^{\infty} (e^x - 1 - h(x)) \phi \nu^P(dx) \right),$$

where $\phi \in L^1(|x|^2 \wedge 1) \nu^P(dx)$, $\phi \geq 0$. To prove that Q is a solution of (5.2), we need to establish that

$$(6.4) \quad \|C^{Q^\phi} - C_M\|_w^2 + \alpha I(Q, P) \leq \|C^{Q_n} - C_M\|_w^2 + \alpha I(Q_n | P).$$

This will be shown in three steps.

Step 1. Let $C_b^{(k)}(\mathbb{R})$ denote the set of continuous bounded functions $\phi : \mathbb{R} \rightarrow \mathbb{R}$ equal to k on some neighborhood of 0: for each $\phi \in C_b^{(k)}(\mathbb{R})$ there exists $\delta > 0$ with $\phi(x) = k$ for all $x : |x| < \delta$. The first step is to prove (6.4) for every $\phi \in C_b^{(1)}$. Choose one such ϕ and let Q_n^ϕ denote an element of $\mathcal{M} \cap \mathcal{L}$ with triplet

$$\left(A_n, \phi \nu_n^P, \gamma_n^\phi := -\frac{A_n}{2} - \int_{-\infty}^{\infty} (e^x - 1 - h(x)) \phi \nu_n^P(dx) \right).$$

Corollary VII.3.6 in [27] and the fact that $P_n \Rightarrow P$ imply that $Q_n^\phi \Rightarrow Q^\phi$, and therefore by Lemma 3.1,

$$\lim_n \|C^{Q_n^\phi} - C_M\|_w^2 = \|C^{Q^\phi} - C_M\|_w^2.$$

Moreover, $\phi \log \phi + 1 - \phi \in C_b^{(0)}(\mathbb{R})$ and $h(\phi - 1) \in C_b^{(0)}(\mathbb{R})$. Therefore, using once again Corollary VII.3.6 in [27], we obtain (here, we use the hypothesis $\lim A_n = A > 0$)

$$\begin{aligned} \lim_n I(Q_n^\phi | P_n) &= \lim_n \frac{T_\infty}{2A_n} \left\{ \gamma_n^\phi - \gamma_n^P - \int_{-\infty}^{\infty} h(x)(\phi - 1) \nu_n^P(dx) \right\}^2 \mathbf{1}_{A_n \neq 0} \\ &\quad + \lim_n T_\infty \int_{-\infty}^{\infty} (\phi \log \phi + 1 - \phi) \nu_n^P(dx) = I(Q^\phi | P). \end{aligned}$$

Lemma A.3 entails that

$$(6.5) \quad I(Q, P) \leq \liminf_n I(Q_n, P_n),$$

and since, by Lemma 3.1, the pricing error is weakly continuous, we have, using the optimality of Q_n ,

$$(6.6) \quad \begin{aligned} \|C^Q - C_M\|_w^2 + \alpha I(Q, P) &\leq \liminf_n \{ \|C^{Q_n} - C_M\|_w^2 + \alpha I(Q_n, P_n) \} \\ &\leq \liminf_n \{ \|C^{Q_n^\phi} - C_M\|_w^2 + \alpha I(Q_n^\phi, P_n) \} = \|C^{Q^\phi} - C_M\|_w^2 + \alpha I(Q^\phi, P). \end{aligned}$$

This proves (6.4) for all $\phi \in C_b^{(1)}(\mathbb{R})$.

Step 2. Let $\phi \in L^1(|x|^2 \wedge 1) \nu^P$ such that $\phi \geq 0$ and $|\phi(x) - 1| \leq C(|x| \wedge 1)$ for every $x \in \mathbb{R}$. Then there exists a sequence $\{\phi_n\} \subset C_b^{(1)}(\mathbb{R})$ such that $\phi_n \rightarrow \phi$ ν^P -a.e. and $|\phi_n(x) - 1| \leq C(|x| \wedge 1)$ for every n and every $x \in \mathbb{R}$. Then by Step 1,

$$(6.7) \quad \|C^Q - C_M\|_w^2 + \alpha I(Q, P) \leq \|C^{Q^{\phi_n}} - C_M\|_w^2 + \alpha I(Q^{\phi_n}, P) \quad \forall n.$$

Using the dominated convergence theorem and Corollary VII.3.6 in [27] yields that $Q^{\phi_n} \Rightarrow Q^\phi$. Since $|h(x)(\phi_n - 1)| \leq Ch(x)(|x| \wedge 1)$ and

$$\phi_n \log \phi_n + 1 - \phi_n \leq (\phi_n - 1)^2 \leq C^2(|x|^2 \wedge 1),$$

the dominated convergence theorem yields

$$\begin{aligned} \lim_n I(Q^{\phi_n} | P_n) &= \lim_n \frac{T_\infty}{2A} \left\{ \gamma^{\phi_n} - \gamma^P - \int_{-\infty}^{\infty} h(x)(\phi_n - 1) \nu^P(dx) \right\}^2 \mathbf{1}_{A \neq 0} \\ &\quad + \lim_n T_\infty \int_{-\infty}^{\infty} (\phi_n \log \phi_n + 1 - \phi_n) \nu^P(dx) = I(Q^\phi | P). \end{aligned}$$

Therefore, by passing to the limit $n \rightarrow \infty$ in (6.7), we obtain that (6.4) holds for every $\phi \in L^1(|x|^2 \wedge 1) \nu^P$ such that $\phi \geq 0$ and $|\phi(x) - 1| \leq C(|x| \wedge 1)$.

Step 3. Let us now choose a nonnegative $\phi \in L^1(|x|^2 \wedge 1) \nu^P$. Without loss of generality, we can assume $I(Q^\phi | P) < \infty$. Let

$$\phi_n(x) = \begin{cases} 1 - n(|x| \wedge 1), & \phi(x) < 1 - n(|x| \wedge 1), \\ 1 + n(|x| \wedge 1), & \phi(x) > 1 + n(|x| \wedge 1), \\ \phi(x) & \text{otherwise.} \end{cases}$$

Then $\phi_n \leq \phi \vee 1$ and, once again, the dominated convergence theorem and Corollary VII.3.6 in [27] entail that $Q^{\phi_n} \Rightarrow Q^\phi$. Since $|h(x)(\phi_n - 1)| \leq |h(x)(\phi - 1)|$ and $\phi_n \log \phi_n + 1 - \phi_n \leq \phi \log \phi + 1 - \phi$, again by dominated convergence we obtain that

$\lim_n I(Q^{\phi_n}|P_n) = I(Q^\phi|P)$ and by passage to the limit $n \rightarrow \infty$ in (6.7), (6.4) holds for all $\phi \in L^1((|x|^2 \wedge 1)\nu^P)$ with $\phi \geq 0$, which completes the proof of the theorem. \square

Another implication of the above theorem is that small changes in the prior Lévy process lead to small changes in the solution: the solution is not very sensitive to minor errors in the determination of the prior measure. This result confirms the empirical observations made in [14].

7. Conclusion. We have proposed here a stable method for constructing an option pricing model of exponential Lévy type, consistent with a given data set of option prices. Our approach is based on the regularization of the calibration problem using the relative entropy with respect to a prior exp-Lévy model as penalization term. The regularization restores existence and stability of solutions; the use of relative entropy links our approach to previous work using relative entropy as a criterion for selection of pricing rules. This technique is readily amenable to numerical implementation, as shown in [14], where empirical applications to financial data are also discussed.

The problem studied here is an example of regularization of a nonlinear, infinite-dimensional inverse problem with noisy data. The above results may also be useful for other nonlinear inverse problems where positivity constraints on the unknown parameter make regularization by relative entropy suitable.

Finally, although we have considered the setting of Lévy processes, this approach can also be adapted to other models with jumps—such as stochastic volatility models with jumps (see [13, Chapter 15] for a review)—where the jump structure is described by a Lévy measure to be retrieved from observations.

Appendix A. Relative entropy for Lévy processes. In this appendix we explicitly compute the relative entropy of two Lévy processes in terms of their characteristic triplets and establish some properties of the relative entropy viewed as a functional on Lévy processes. Under additional assumptions the relative entropy of two Lévy processes was computed in [11] in the case where Q is equivalent to P and the Lévy process has finite exponential moments under P and in [30] in the case where $\log \frac{d\nu^Q}{d\nu^P}$ is bounded. We give here an elementary proof valid for all Lévy processes.

THEOREM A.1 (relative entropy of Lévy processes). *Let $\{X_t\}_{t \geq 0}$ be a real-valued Lévy process on (Ω, \mathcal{F}, Q) and on (Ω, \mathcal{F}, P) with respective characteristic triplets (A_Q, ν_Q, γ_Q) and (A_P, ν_P, γ_P) . Suppose that $Q \ll P$ (by Theorem IV.4.39 in [27], this implies that $A^Q = A^P$ and $\nu^Q \ll \nu^P$) and denote $A := A_Q = A_P$. Then for every time horizon $T \leq T_\infty$ the relative entropy of $Q|_{\mathcal{F}_T}$ with respect to $P|_{\mathcal{F}_T}$ can be computed as follows:*

$$(A.1) \quad I_T(Q|P) = I(Q|_{\mathcal{F}_T}|P|_{\mathcal{F}_T}) = \frac{T}{2A} \left\{ \gamma^Q - \gamma^P - \int_{-1}^1 x(\nu^Q - \nu^P)(dx) \right\}^2 \mathbf{1}_{A \neq 0} \\ + T \int_{-\infty}^{\infty} \left(\frac{d\nu^Q}{d\nu^P} \log \frac{d\nu^Q}{d\nu^P} + 1 - \frac{d\nu^Q}{d\nu^P} \right) \nu^P(dx).$$

Proof. Let $\{X_t^c\}_{t \geq 0}$ be the continuous martingale part of X under P (a Brownian motion), μ be the jump measure of X , and $\phi := \frac{d\nu^Q}{d\nu^P}$. From [27, Theorem III.5.19], the density process $Z_t := \frac{dQ|_{\mathcal{F}_t}}{dP|_{\mathcal{F}_t}}$ is the Doléans-Dade exponential of the Lévy process $\{N_t\}_{t \geq 0}$ defined by

$$N_t := \beta X_t^c + \int_{[0,t] \times \mathbb{R}} (\phi(x) - 1) \{ \mu(ds \times dx) - ds \nu^P(dx) \},$$

where β is given by

$$\beta = \begin{cases} \frac{1}{A} \{ \gamma^Q - \gamma^P - \int_{|x| \leq 1} x(\phi(x) - 1) \nu^P(dx) \} & \text{if } A > 0, \\ 0 & \text{otherwise.} \end{cases}$$

Choose $0 < \varepsilon < 1$ and let $I := \{x : \varepsilon \leq \phi(x) \leq \varepsilon^{-1}\}$. We split N_t into two independent martingales:

$$\begin{aligned} N'_t &:= \beta X_t^c + \int_{[0,t] \times I} (\phi(x) - 1) \{ \mu(ds \times dx) - ds \nu^P(dx) \} \quad \text{and} \\ N''_t &:= \int_{[0,t] \times (\mathbb{R} \setminus I)} (\phi(x) - 1) \{ \mu(ds \times dx) - ds \nu^P(dx) \}. \end{aligned}$$

Since N' and N'' never jump together, $[N', N'']_t = 0$ and $\mathcal{E}(N' + N'')_t = \mathcal{E}(N')_t \mathcal{E}(N'')_t$ (cf. equation II.8.19 in [27]). Moreover, since N' and N'' are Lévy processes and martingales, their stochastic exponentials are also martingales (Proposition 8.23 in [13]). Therefore,

$$\begin{aligned} I_T(Q|P) &= E^P[Z_T \log Z_T] \\ &= E^P[\mathcal{E}(N')_T \mathcal{E}(N'')_T \log \mathcal{E}(N')_T] + E^P[\mathcal{E}(N')_T \mathcal{E}(N'')_T \log \mathcal{E}(N'')_T] \\ \text{(A.2)} \quad &= E^P[\mathcal{E}(N')_T \log \mathcal{E}(N')_T] + E^P[\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T] \end{aligned}$$

if these expectations exist.

Since $\Delta N'_t > -1$ a.s., $\mathcal{E}(N')_t$ is almost surely positive. Therefore, from Lemma 5.8 in [23], $U_t := \log \mathcal{E}(N')_t$ is a Lévy process with the following characteristic triplet:

$$\begin{aligned} A^U &= \beta^2 A, \\ \nu^U(B) &= \nu^P(I \cap \{x : \log \phi(x) \in B\}) \quad \forall B \in \mathcal{B}(\mathbb{R}), \\ \gamma^U &= -\frac{\beta^2 A}{2} - \int_{-\infty}^{\infty} (e^x - 1 - x 1_{|x| \leq 1}) \nu^U(dx). \end{aligned}$$

This implies that U has bounded jumps and all exponential moments. Therefore, $E[U_T e^{U_T}] < \infty$ and can be computed as follows:

$$\begin{aligned} E^P[U_T e^{U_T}] &= -i \frac{d}{dz} E^P[e^{izU_T}]|_{z=-i} = -iT \psi'(-i) E^P[e^{U_T}] = -iT \psi'(-i) \\ &= T \left(A^U + \gamma^U + \int_{-\infty}^{\infty} (x e^x - x 1_{|x| \leq 1}) \nu^U(dx) \right) \\ \text{(A.3)} \quad &= \frac{\beta^2 AT}{2} + T \int_I (\phi(x) \log \phi(x) + 1 - \phi(x)) \nu^P(dx). \end{aligned}$$

It remains to compute $E^P[\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T]$. Since N'' is a compound Poisson process, $\mathcal{E}(N'')_t = e^{bt} \prod_{s \leq t} (1 + \Delta N''_s)$, where $b = \int_{\mathbb{R} \setminus I} (1 - \phi(x)) \nu^P(dx)$. Let ν'' be the Lévy measure of N'' and λ its jump intensity. Then

$$\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T = bT \mathcal{E}(N'')_T + e^{bT} \prod_{s \leq T} (1 + \Delta N''_s) \sum_{s \leq T} \log(1 + \Delta N''_s)$$

and

$$\begin{aligned} &E^P[\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T] \\ &= bT + e^{bT} \sum_{k=0}^{\infty} e^{-\lambda T} \frac{(\lambda T)^k}{k!} E \left[\prod_{s \leq T} (1 + \Delta N''_s) \sum_{s \leq T} \log(1 + \Delta N''_s) \mid k \text{ jumps} \right]. \end{aligned}$$

Since, under the condition that N'' jumps exactly k times in the interval $[0, T]$, the jump sizes are independent and identically distributed, we find, denoting the generic jump size by $\Delta N''$,

$$\begin{aligned}
& E^P[\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T] \\
&= bT + e^{bT} \sum_{k=0}^{\infty} e^{-\lambda T} \frac{(\lambda T)^k}{k!} k E[1 + \Delta N'']^{k-1} E[(1 + \Delta N'') \log(1 + \Delta N'')] \\
&= bT + \lambda T E[(1 + \Delta N'') \log(1 + \Delta N'')] \\
&= bT + T \int_{-\infty}^{\infty} (1+x) \log(1+x) \nu''(dx) \\
&= T \int_{\mathbb{R} \setminus I} (\phi(x) \log \phi(x) + 1 - \phi(x)) \nu^P(dx).
\end{aligned}$$

In particular, $E^P[\mathcal{E}(N'')_T \log \mathcal{E}(N'')_T]$ is finite if and only if the integral in the last line is finite. Combining the above expression with (A.3) and (A.2) finishes the proof. \square

LEMMA A.2. *Let $P, \{P_n\}_{n \geq 1} \subset \mathcal{L}_B^+$ for some $B > 0$, such that $P_n \Rightarrow P$. Then for every $r > 0$, the level set $L_r := \{Q \in \mathcal{L} : I(Q|P_n) \leq r \text{ for some } n\}$ is tight.*

Proof. For every $Q \in L_r$, choose any element of $\{P_n\}_{n \geq 1}$ for which $I(Q|P_n) \leq r$ and denote it by P_Q . The characteristic triplet of Q is denoted by (A^Q, ν^Q, γ^Q) and that of P_Q by $(A^{P_Q}, \nu^{P_Q}, \gamma^{P_Q})$. In addition, we define $\phi^Q := \frac{d\nu^Q}{d\nu^{P_Q}}$. From Theorem A.1,

$$\int_{-\infty}^{\infty} (\phi^Q(x) \log \phi^Q(x) + 1 - \phi^Q(x)) \nu^{P_Q}(dx) \leq r/T_{\infty}.$$

Therefore, for u sufficiently large,

$$\int_{\{\phi^Q > u\}} \phi^Q \nu^{P_Q}(dx) \leq \int_{\{\phi^Q > u\}} \frac{2\phi^Q[\phi^Q \log \phi^Q + 1 - \phi^Q] \nu^{P_Q}(dx)}{\phi^Q \log \phi^Q} \leq \frac{2r}{T_{\infty} \log u},$$

which entails that for u sufficiently large,

$$\int_{\{\phi^Q > u\}} \nu^Q(dx) \leq \frac{2r}{T_{\infty} \log u}$$

uniformly with respect to $Q \in L_r$. Let $\varepsilon > 0$ and choose u such that $\int_{\{\phi^Q > u\}} \nu^Q(dx) \leq \varepsilon/2$ for every $Q \in L_r$. By Corollary VII.3.6 in [27],

$$\int_{-\infty}^{\infty} f(x) \nu^{P_n}(dx) \rightarrow \int_{-\infty}^{\infty} f(x) \nu^P(dx)$$

for every continuous bounded function f that is identically zero on a neighborhood of zero. Since the measures ν^P and ν^{P_n} for all $n \geq 1$ are finite outside a neighborhood of zero and $P_n \Rightarrow P$, we can choose a compact K such that $\nu^{P_n}(\mathbb{R} \setminus K) \leq \varepsilon/2u$ for every n . Then

$$(A.4) \quad \nu^Q(\mathbb{R} \setminus K) = \int_{(\mathbb{R} \setminus K) \cap \{\phi^Q \leq u\}} \phi^Q \nu^{P_Q}(dx) + \int_{(\mathbb{R} \setminus K) \cap \{\phi^Q > u\}} \nu^Q(dx) \leq \varepsilon.$$

It is easy to check by computing derivatives that for every $u > 0$, on the set $\{x : \phi^Q(x) \leq u\}$,

$$(\phi^Q - 1)^2 \leq 2u(\phi^Q \log \phi^Q + 1 - \phi^Q).$$

Therefore, for u sufficiently large and for all $Q \in L_r$,

$$\begin{aligned}
& \left| \int_{|x| \leq 1} x(\phi^Q - 1) \nu^{P_Q}(dx) \right| \\
& \leq \left| \int_{|x| \leq 1, \phi^Q \leq u} x(\phi^Q - 1) \nu^{P_Q}(dx) \right| + \left| \int_{|x| \leq 1, \phi^Q > u} x(\phi^Q - 1) \nu^{P_Q}(dx) \right| \\
& \leq \int_{|x| \leq 1} x^2 \nu^{P_Q}(dx) + \int_{|x| \leq 1, \phi^Q \leq u} (\phi^Q - 1)^2 \nu^{P_Q}(dx) + 2 \int_{\phi^Q > u} \phi^Q \nu^{P_Q}(dx) \\
& \leq \int_{|x| \leq 1} x^2 \nu^{P_Q}(dx) + 2u \int_{-\infty}^{\infty} (\phi^Q \log \phi^Q + 1 - \phi^Q) \nu^{P_Q}(dx) + \frac{4r}{T_\infty \log u} \\
\text{(A.5)} \quad & \leq \int_{|x| \leq 1} x^2 \nu^{P_Q}(dx) + \frac{3ru}{T_\infty}.
\end{aligned}$$

By Proposition VI.4.18 in [27], the tightness of $\{P_n\}_{n \geq 1}$ implies that

$$\text{(A.6)} \quad A^{P_n} + \int_{|x| \leq 1} x^2 \nu^{P_n}(dx)$$

is bounded uniformly on n , which means that the right-hand side of (A.5) is bounded uniformly with respect to $Q \in L_r$. From Theorem IV.4.39 in [27], $A^Q = A^{P_Q}$ for all $Q \in L_r$ because for the relative entropy to be finite, necessarily $Q \ll P_Q$. Theorem A.1 then implies that

$$\left\{ \gamma^Q - \gamma^P - \int_{-1}^1 x(\nu^Q - \nu^P)(dx) \right\}^2 \leq \frac{2A^{P_Q}r}{T_\infty}.$$

From (A.6), A^{P_n} is bounded uniformly on n . Therefore, inequality (A.5) shows that $|\gamma^Q|$ is bounded uniformly with respect to Q . For u sufficiently large,

$$\begin{aligned}
\text{(A.7)} \quad A^Q + \int_{-\infty}^{\infty} (x^2 \wedge 1) \phi^Q \nu^{P_Q}(dx) & \leq A^Q + u \int_{\phi^Q \leq u} (x^2 \wedge 1) \nu^{P_Q}(dx) \\
& + \int_{\phi^Q > u} \phi^Q \nu^{P_Q}(dx) \leq A^{P_Q} + u \int_{-\infty}^{\infty} (x^2 \wedge 1) \nu^{P_Q}(dx) + \frac{2r}{T_\infty \log u}
\end{aligned}$$

and (A.6) implies that the right-hand side is bounded uniformly with respect to $Q \in L_r$. By Proposition VI.4.18 in [27], (A.4), (A.7), and the fact that $|\gamma^Q|$ is bounded uniformly with respect to Q entail that the set L_r is tight. \square

LEMMA A.3. *Let Q and P be two probability measures on (Ω, \mathcal{F}) . Then*

$$\text{(A.8)} \quad I(Q|P) = \sup_{f \in C_b(\Omega)} \left\{ \int_{\Omega} f dQ - \int_{\Omega} (e^f - 1) dP \right\},$$

where $C_b(\Omega)$ is space of bounded continuous functions on Ω .

Proof. Observe that

$$\phi(x) = \begin{cases} x \log x + 1 - x, & x > 0, \\ \infty, & x \leq 0, \end{cases}$$

and $\phi^*(y) = e^y - 1$ are proper convex functions on \mathbb{R} , conjugate to each other, and apply Corollary 2 in [31, p. 538]. \square

COROLLARY A.4. *The relative entropy functional $I(Q|P)$ is weakly lower semi-continuous with respect to Q for fixed P .*

LEMMA A.5. *Let $P, \{P_n\}_{n \geq 1} \subset \mathcal{L}_{NA} \cap \mathcal{L}_B^+$ for some $B > 0$ such that $P_n \Rightarrow P$. There exists a sequence $\{Q_n\}_{n \geq 1} \subset \mathcal{M} \cap \mathcal{L}_B^+$ with $Q_n \sim P_n$ for every n and a constant $C < \infty$ such that $I(Q_n|P_n) \leq C$ for every n .*

Proof. Let $h : \mathbb{R} \rightarrow \mathbb{R}$ be a continuous truncation function. For $n \geq 1$, let (A_n, ν_n, γ_n) be the characteristic triplet of P_n with respect to h and let

$$f(\beta, P_n) := \gamma_n + \left(\frac{1}{2} + \beta\right) A_n + \int_{-\infty}^{\infty} \left\{ (e^x - 1)e^{\beta(e^x - 1)} - h(x) \right\} \nu_n(dx).$$

The first step is to show that for every n , there exists a unique β_n such that $f(\beta_n, P_n) = 0$ and that the sequence $\{\beta_n\}_{n \geq 1}$ is bounded.

Since for every n , $P_n \in \mathcal{L}_B^+$, the dominated convergence theorem yields

$$f'_\beta(\beta, P_n) = A_n + \int_{-\infty}^{\infty} (e^x - 1)^2 e^{\beta(e^x - 1)} \nu_n(dx) > 0,$$

and since $P_n \in \mathcal{L}_{NA}$, the Lévy process (X, P_n) is not a.s. increasing or a.s. decreasing, which means that at least one of the following conditions holds:

1. $A_n > 0$,
2. $\nu_n((-\infty, 0)) > 0$ and $\nu_n(0, \infty) > 0$,
3. $A_n = 0$, $\nu_n((-\infty, 0)) = 0$ and $\gamma_n - \int_{-\infty}^{\infty} h(x) \nu_n(dx) < 0$,
4. $A_n = 0$, $\nu_n((0, \infty)) = 0$ and $\gamma_n - \int_{-\infty}^{\infty} h(x) \nu_n(dx) > 0$.

Since $f'_\beta(\beta, P_n) \geq A_n + \min(\int_{-\infty}^0 (e^x - 1)^2 \nu_n(dx), \int_0^\infty (e^x - 1)^2 \nu_n(dx))$, if conditions 1 or 2 above hold, $f'_\beta(\beta, P_n)$ is bounded from below by a positive constant and therefore

$$(A.9) \quad \exists! \beta_n : f(\beta_n, P_n) = 0.$$

If condition 3 above holds, $\lim_{\beta \rightarrow -\infty} f(\beta, P_n) = \gamma_n - \int_{-\infty}^{\infty} h(x) \nu_n(dx) < 0$ and $\lim_{\beta \rightarrow \infty} f(\beta, P_n) = \infty$, which means that (A.9) also holds. The case when condition 4 above is satisfied may be treated similarly.

Let us now show that the sequence $\{\beta_n\}_{n \geq 1}$ is bounded. Rewrite $f(\beta, P_n)$ as

$$(A.10) \quad \begin{aligned} f(\beta, P_n) := & \gamma_n + \left(\frac{1}{2} + \beta\right) \left(A_n + \int_{-\infty}^{\infty} h^2(x) \nu_n(dx) \right) \\ & + \int_{-\infty}^{\infty} \left\{ (e^x - 1)e^{\beta(e^x - 1)} - h(x) - \left(\frac{1}{2} + \beta\right) h^2(x) \right\} \nu_n(dx). \end{aligned}$$

Since $(e^x - 1)e^{\beta(e^x - 1)} - x - \left(\frac{1}{2} + \beta\right) x^2 = o(|x|^2)$ and the integrand in the last term of (A.10) is bounded on $(-\infty, B]$, by Corollary VII.3.6 in [27], for every β , $\lim_n f(\beta, P_n) = f(\beta, P)$.

Since P also belongs to $\mathcal{L}_B^+ \cap \mathcal{L}_{NA}$, by the same argument as above, there exists a unique β^* such that $f(\beta^*, P) = 0$ and $f'_\beta(\beta^*, P) > 0$. This means that there exist $\varepsilon > 0$ and finite constants $\beta_- < \beta^*$ and $\beta_+ > \beta^*$ such that $f(\beta_-, P) < -\varepsilon$ and $f(\beta_+, P) > \varepsilon$. One can then find N such that for all $n \geq N$, $f(\beta_-, P_n) < -\varepsilon/2$ and $f(\beta_+, P_n) > \varepsilon/2$, which means that $\beta_n \in [\beta_-, \beta_+]$ and the sequence $\{\beta_n\}$ is bounded. Let (X, Q_n) be the Lévy process with characteristic triplet (with respect to h)

$$\begin{aligned} A_n^Q &= A_n, & \nu_n^Q &= e^{\beta_n(e^x - 1)} \nu_n, \\ \gamma_n^Q &= \gamma_n + A_n \beta_n + \int_{-\infty}^{\infty} h(x) (e^{\beta_n(e^x - 1)} - 1) \nu_n(dx). \end{aligned}$$

The measure Q_n is in fact the minimal entropy martingale measure for P_n [29], but this result is not used here. From Theorem A.1,

$$(A.11) \quad I(Q_n|P_n) = -T \left\{ \frac{\beta_n}{2} (1 + \beta_n) A_n + \beta_n \gamma_n + \int_{-\infty}^{\infty} \{e^{\beta_n(e^x-1)} - 1 - \beta_n h(x)\} \nu_n(dx) \right\}.$$

To show that the sequence $\{I(Q_n|P_n)\}_{n \geq 1}$ is bounded, observe that for

$$\begin{aligned} \forall x \in [-1, 1], \quad & \left| e^{\beta(e^x-1)} - 1 - \beta x \right| \leq \beta e^{\beta(e-1)+1} (1 + \beta e) |x|^2, \\ \forall x \leq B, \quad & \left| e^{\beta(e^x-1)} - 1 - \beta x 1_{|x| \leq 1} \right| \leq \beta e^{\beta(e^B+1)} + 1 + \beta B. \end{aligned}$$

The uniform boundedness of the sequence of relative entropies now follows from (A.11) and Theorem VI.4.18 in [27]. \square

REFERENCES

- [1] Y. ACHDOU, *An inverse problem for a parabolic variational inequality arising in volatility calibration with American options*, SIAM J. Control Optim., 43 (2005), pp. 1583–1615.
- [2] L. ANDERSEN AND J. ANDREASEN, *Jump-diffusion models: Volatility smile fitting and numerical methods for pricing*, Rev. Derivatives Research, 4 (2000), pp. 231–262.
- [3] M. AVELLANEDA, *The minimum-entropy algorithm and related methods for calibrating asset-pricing models*, in Proceedings of the International Congress of Mathematicians, (Berlin, 1998), Vol. III, Documenta Mathematica, 1998, pp. 545–563.
- [4] M. AVELLANEDA, *Minimum entropy calibration of asset pricing models*, Internat. J. Theoret. Appl. Finance, 1 (1998), pp. 447–472.
- [5] M. AVELLANEDA, R. BUFF, C. FRIEDMAN, N. GRANDCHAMP, L. KRUK, AND J. NEWMAN, *Weighted Monte Carlo: A new technique for calibrating asset-pricing models*, Internat. J. Theoret. Appl. Finance, 4 (2001), pp. 91–119.
- [6] M. AVELLANEDA, C. FRIEDMAN, R. HOLMES, AND D. SAMPERI, *Calibrating volatility surfaces via relative entropy minimization*, Appl. Math. Finance, 4 (1997), pp. 37–64.
- [7] H. BANKS AND K. KUNISCH, *Estimation Techniques for Distributed Parameter Systems*, Birkhauser Boston, Cambridge, MA, 1989.
- [8] D. BATES, *Jumps and stochastic volatility: The exchange rate processes implicit in Deutschemark options*, Rev. Fin. Studies, 9 (1996), pp. 69–107.
- [9] S. BEN HAMIDA AND R. CONT, *Recovering volatility from option prices by evolutionary optimization*, J. Comput. Finance, 8 (2005), pp. 43–76.
- [10] P. CARR AND D. MADAN, *Option valuation using the fast Fourier transform*, J. Comput. Finance, 2 (1998), pp. 61–73.
- [11] T. CHAN, *Pricing contingent claims on stocks driven by Lévy processes*, Ann. Appl. Probab., 9 (1999), pp. 504–528.
- [12] R. CONT, *Model uncertainty and its impact on the pricing of derivative instruments*, Math. Finance, to appear.
- [13] R. CONT AND P. TANKOV, *Financial Modelling with Jump Processes*, Chapman and Hall/CRC Press, Boca Raton, FL, 2004.
- [14] R. CONT AND P. TANKOV, *Non-parametric calibration of jump-diffusion option pricing models*, J. Comput. Finance, 7 (2004), pp. 1–49.
- [15] R. CONT AND E. VOLTCHKOVA, *A finite difference scheme for option pricing in jump diffusion and exponential Lévy models*, SIAM J. Numer. Anal., 43 (2005), pp. 1596–1626.
- [16] S. CRÉPEY, *Calibration of the local volatility in a trinomial tree using Tikhonov regularization*, Inverse Problems, 19 (2003), pp. 91–127.
- [17] I. CSISZAR, *I-divergence geometry of probability distributions and minimization problems*, Ann. Probab., 3 (1975), pp. 146–158.
- [18] B. DUPIRE, *Pricing with a smile*, RISK, 7 (1994), pp. 18–20.
- [19] N. EL KAROUI AND R. ROUGE, *Pricing via utility maximization and entropy*, Math. Finance, 10 (2000), pp. 259–276.
- [20] H. W. ENGL, M. HANKE, AND A. NEUBAUER, *Regularization of Inverse Problems*, Math. Appl. 375, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.

- [21] H. W. ENGL AND G. LANDL, *Convergence rates for maximum entropy regularization*, SIAM J. Numer. Anal., 30 (1993), pp. 1509–1536.
- [22] M. FRITTELLI, *The minimal entropy Martingale measure and the valuation problem in incomplete markets*, Math. Finance, 10 (2000), pp. 39–52.
- [23] T. GOLL AND J. KALLSEN, *Optimal portfolios for logarithmic utility*, Stochastic Process. Appl., 89 (2000), pp. 31–48.
- [24] T. GOLL AND L. RÜSCHENDORF, *Minimal distance Martingale measures and optimal portfolios consistent with observed market prices*, in Stochastic Processes and Related Topics (Siegmundsburg, 2000), Stochastics Monogr. 12, Taylor and Francis, London, 2002, pp. 141–154.
- [25] J. M. HARRISON AND S. R. PLISKA, *Martingales and stochastic integrals in the theory of continuous trading*, Stochastic Process. Appl., 11 (1981), pp. 215–260.
- [26] N. JACKSON, E. SÜLLI, AND S. HOWISON, *Computation of deterministic volatility surfaces*, J. Comput. Finance, 2 (1999), pp. 5–32.
- [27] J. JACOD AND A. N. SHIRYAEV, *Limit Theorems for Stochastic Processes*, 2nd ed., Springer, Berlin, 2003.
- [28] R. LAGNADO AND S. OSHER, *A technique for calibrating derivative security pricing models: Numerical solution of the inverse problem*, J. Comput. Finance, 1 (1997), pp. 13–25.
- [29] Y. MIYAHARA AND T. FUJIWARA, *The minimal entropy martingale measures for geometric Lévy processes*, Finance Stoch., 7 (2003), pp. 509–531.
- [30] L. NGUYEN, *Calibration de Modèles Financiers par Minimisation d'Entropie Relative et Modèles avec Sauts*, Ph.D. thesis, Ecole Nationale de Ponts et Chaussées, Paris, France, 2003.
- [31] R. T. ROCKAFELLAR, *Integrals which are convex functionals*, Pacific J. Math., 24 (1968), pp. 525–539.
- [32] M. RUBINSTEIN, *Implied binomial trees*, J. Finance, 49 (1994), pp. 771–819.
- [33] D. SAMPERI, *Calibrating a diffusion pricing model with uncertain volatility: Regularization and stability*, Math. Finance, 12 (2002), pp. 71–87.
- [34] K. SATO, *Lévy Processes and Infinitely Divisible Distributions*, Cambridge University Press, Cambridge, UK, 1999.
- [35] M. STUTZER, *A simple nonparametric approach to derivative security valuation*, J. Finance, 51 (1996), pp. 1633–1652.
- [36] P. TANKOV, *Lévy Processes in Finance: Inverse Problems and Dependence Modelling*, Ph.D. thesis, Ecole Polytechnique, Palaiseau, France, 2004.