A limit theorem for likelihoods in the LAQ case

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Density processes

Let

$$\mathbb{E}^n = (\Omega^n, \mathscr{F}^n, \mathbb{F}^n = (\mathscr{F}^n_t)_{0\leqslant t\leqslant 1}, (\mathsf{P}^{n,\vartheta})_{\vartheta\in\Theta\subseteq\mathbb{R}^k})$$

be a sequence of filtered statistical models, $\mathscr{F}^n = \mathscr{F}^n_1$.
If T is an $\mathbb{F}^n$-stopping time then $\mathsf{P}^{n,\vartheta}_T := \mathsf{P}^{n,\vartheta}\big|_{\mathscr{F}^n_T}$.
For simplicity we shall assume that, for every n, $\mathsf{P}^{n,\vartheta}$ coincide on $\mathscr{F}^n_0$ for different ϑ.
Let a point $\vartheta_0 \in \operatorname{int}\Theta$ and a sequence of nonsingular (normalizing) $k \times k$-matrices $\varphi_n \to 0$ be given.
Let $Z^{n,\vartheta}$ be the density process of $\mathsf{P}^{n,\vartheta_0+\varphi_n\vartheta}$ with respect to $\mathsf{P}^n := \mathsf{P}^{n,\vartheta_0}$, i.e. a càdlàg $\mathbb{F}^n$-adapted process $(Z^{n,\vartheta}_t)_{t\leqslant 1}$ with values in $\mathbb{R}_+$ such that, for any $\mathbb{F}^n$-stopping time T, $Z^{n,\vartheta}_T$ is the density of the absolutely continuous part of $\mathsf{P}^{n,\vartheta_0+\varphi_n\vartheta}_T$ with respect to P^n_T. In general, $Z^{n,\vartheta}$ is a P^n-supermartingale.

Objectives

It is important in statistics to find a normalizing sequence of matrices φ_n such that the random function $\left(Z_1^{n,\vartheta},\ \vartheta \in \varphi_n^{-1}(\Theta - \{\vartheta_0\})\right)$ converges in distribution (wrt P^n) to a nondegenerate random function $(Z_1^{\vartheta},\ \vartheta \in \mathbb{R}^k)$ (at least, finite-dimensional convergence).

We are interested in the case where we have weak convergence of $\left(Z_t^{n,\vartheta},\ t \in [0,1],\ \vartheta \in \varphi_n^{-1}(\Theta - \{\vartheta_0\})\right)$ (wrt P^n) to $(Z_t^{\vartheta},\ t \in [0,1],\ \vartheta \in \mathbb{R}^k)$ (uniform finite-dimensional in ϑ and functional in t), and

$$Z_t^{\vartheta} = \exp\Big(\vartheta^\top M_t - \frac{1}{2}\vartheta^\top \langle M\rangle_t \vartheta\Big),$$

where $M = (M_t)$ is a continuous local martingale and is not a Gaussian or a conditionally Gaussian martingale.

Outline

Jacod and Shiryaev (1987)

$(\Omega^n, \mathscr{F}^n, \mathbb{F}^n, (\mathsf{P}^n, \mathsf{P}'^n))$ sequence of binary experiments
Z^n is the density process of P'^n wrt P^n.

Assumptions on the limiting model

- $\Omega = \mathbb{D}(\mathbb{R}) = \mathbb{D}(\mathbb{R}_+; \mathbb{R})$ is the Skorokhod space with the Borel σ-field $\mathscr{F}$ and the filtration $\mathbb{F} = \mathscr{D}(\mathbb{R})$ generated by the canonical process denoted by X.
- C is an adapted continuous increasing process with $C_0 = 0$, defined on $(\Omega, \mathscr{F}, \mathbb{F})$.
- There is a continuous increasing function $t \rightsquigarrow F_t$ with $F_0 = 0$, such that $F - C(\alpha)$ is nondecreasing for all $\alpha \in \Omega$.
- $\alpha \rightsquigarrow C_t(\alpha)$ is Skorokhod-continuous for all $t \in \mathbb{R}_+$.
- There is a unique probability measure P on $(\Omega, \mathscr{F})$ under which $M := X + C/2$ is a continuous local martingale with $M_0 = 0$ and $\langle M \rangle = C$.

Assumptions on convergence

Under these assumptions there exists a unique measure P' on $(\Omega, \mathscr{F})$ under which $M' := X - C/2$ is a continuous local martingale with $M'_0 = 0$ and $\langle M' \rangle = C$. Moreover, $\mathrm{P}' \overset{\text{loc}}{\ll} P$, and the density process of P' with respect to P is e^X. In particular, e^X is a P-martingale.

Assumptions on convergence

- $h^n_t - \frac{1}{8} C_t \circ \log(Z^n \vee \frac{1}{n}) \xrightarrow{\mathrm{P}^n} 0$, $n \to \infty$, $t \in \mathbb{R}_+$, where h^n is the Hellinger process of order $1/2$ for P^n and P'^n;
- Lindeberg-type condition on the jumps of Z^n;
- $\iota^n_t \xrightarrow{\mathrm{P}^n} 0, \quad n \to \infty$, for all $t \in \mathbb{R}_+$, where ι^n is the Hellinger process of order 0 for P^n and P'^n.

Theorem X.1.59 in Jacod and Shiryaev (1987)

Theorem

Let assumptions on the limiting model be satisfied. If assumptions on convergence hold true, then

$$\mathscr{L}(Z^n \mid \mathsf{P}^n) \xrightarrow{\mathbb{D}(\mathbb{R})} \mathscr{L}(e^X \mid \mathsf{P}), \quad n \to \infty.$$

Conversely, if

$$\mathscr{L}(Z^n \mid \mathsf{P}^n) \xrightarrow{d_f} \mathscr{L}(e^X \mid \mathsf{P}), \quad n \to \infty,$$

then assumptions on convergence are satisfied.

Gushchin and Valkeila (2003)

A similar result was proved in Gushchin and Valkeila (2003). The differences in assumptions on the limiting model are:

- Now the canonical process is denoted by M.
- There is a unique probability measure P on $(\Omega, \mathscr{F})$ under which M is a continuous local martingale with $M_0 = 0$ and $\langle M \rangle = C$.

Under these assumptions there exists a unique measure P' on $(\Omega, \mathscr{F})$ under which $M' := M - C$ is a continuous local martingale with $M'_0 = 0$ and $\langle M' \rangle = C$. Moreover, $\mathrm{P}' \overset{\text{loc}}{\ll} P$, and the density process of P' with respect to P is $e^{M - C/2}$.
The statement of the theorem is essentially the same.

Luschgy (1994)

- A semimartingale $X = (X_t)_{t\in\mathbb{R}_+}$ with predictable characteristics $T(\vartheta) = (B(\vartheta), C, \nu(\vartheta))$ is observed on $[0, T]$. It is quasi-left-continuous. Asymptotics: $T \to \infty$.
- The density process of P^η with respect to P^ϑ is expressed (in a standard way) via characteristics.
- Characteristics are "asymptotically differentiable" in ϑ in accordance with a normalizing sequence $\{\varphi_n\}$, and an "asymptotic score process" (at ϑ) is defined and is a locally square-integrable martingale wrt P^ϑ. As a consequence, this asymptotic score process provides a linear-quadratic approximation for the log-likelihood processes.
- It is assumed that, after rescaling in time, the asymptotic score process weakly converges to a continuous local martingale.

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Prerequisites for the limiting model. 1

- $\Omega = \mathbb{D}(\mathbb{R}^q)$ is the Skorokhod space with the Borel σ-field $\mathscr{F}$ and the filtration $\mathbb{F} = \mathscr{D}(\mathbb{R}^q)$ generated by the canonical process denoted by B.
- $C = (C^{ij})_{i,j \leqslant q}$ is an adapted continuous increasing process with values in the set $\mathbb{M}_+^q$ of all symmetric positive semidefinite $q \times q$ matrices, defined on $(\Omega, \mathscr{F}, \mathbb{F})$, $C_0 = 0$.
- There is a continuous and deterministic increasing function $t \rightsquigarrow F_t$ with $F_0 = 0$, such that $F - \sum_{i=1}^q C^{ii}(\alpha)$ is nondecreasing for all $\alpha \in \Omega$.
- $\alpha \rightsquigarrow C_t(\alpha)$ is Skorokhod-continuous for all $t \in \mathbb{R}_+$.
- There is a unique probability measure P on $(\Omega, \mathscr{F})$ under which B is a continuous local martingale with $B_0 = 0$ and $\langle B \rangle = C$.

Prerequisites for the limiting model. 2

The second component for constructing our limiting model is given by

- There are adapted càdlàg processes $G^n = (G^{n,ij})_{i\leqslant k,\, j\leqslant q}$ and $G = (G^{ij})_{i\leqslant k,\, j\leqslant q}$ with values in $\mathbb{R}^{k\times q}$, defined on $(\Omega, \mathscr{F}, \mathbb{F})$.
- If $\alpha_n \to \alpha \in \mathbb{C}(\mathbb{R}^q)$ in the Skorokhod topology on $\mathbb{D}(\mathbb{R}^q)$ (i.e. locally uniformly), then $G^n(\alpha_n) \to G(\alpha)$ in the Skorokhod topology on $\mathbb{D}(\mathbb{R}^{k\times q})$.

Some notation

There is a predictable process $c = (c^{ij})_{i,j \leqslant q}$ with values in $\mathbb{M}_+^q$, defined on $(\Omega, \mathscr{F}, \mathbb{F})$, such that $C_t^{ij} = c^{ij} \cdot F_t$, $i, j \leqslant q$, and $\mathrm{trace}(c_t) \leqslant 1$ for all $t \in \mathbb{R}_+$ P-a.s.

In what follows we use the notation $G^n \circ B^n$, which is understood as the composition of the mappings $B^n \colon \Omega^n \to \Omega$ and $G^n \colon \Omega \to \mathbb{D}(\mathbb{R}^{k \times q})$. Note that $G \circ B = G$.

For a $(k \times q)$-dimensional adapted càdlàg process $H = (H^{ij})_{i \leqslant k,\, j \leqslant q}$ and a q-dimensional locally square-integrable martingale $N = (N^j)_{j \leqslant q}$ the process $Y := H_- \cdot N$ is understood as a k-dimensional locally square-integrable martingale $Y = (Y^i)_{i \leqslant k}$ such that $Y^i = \sum_{j=1}^q H_-^{ij} \cdot N^j$.

Limiting process

Now we are in a position to describe our limiting process. Put

$$K := G \circ B = G$$

and

$$M := K_- \cdot B,$$

then M is a k-dimensional locally square-integrable martingale with the quadratic characteristic

$$\langle M \rangle = (G_- c G_-^\top) \cdot F.$$

Now we define the limiting process Z^ϑ by

$$Z_t^\vartheta = \exp\Big(\vartheta^\top M_t - \frac{1}{2}\vartheta^\top \langle M \rangle_t \vartheta\Big).$$

Some extra notation. 1

Recall that we deal with a sequence

$$\mathbb{E}^n = (\Omega^n, \mathscr{F}^n, \mathbb{F}^n = (\mathscr{F}^n_t)_{t\leqslant 1}, (\mathsf{P}^{n,\vartheta})_{\vartheta\in\Theta\subseteq\mathbb{R}^k})$$

of filtered statistical models, and $Z^{n,\vartheta}$ is the density process of $\mathsf{P}^{n,\vartheta_0+\varphi_n\vartheta}$ with respect to $\mathsf{P}^n := \mathsf{P}^{n,\vartheta_0}$.
Put $Y^{n,\vartheta} := \sqrt{Z^{n,\vartheta}}$, then the process $Y^{n,\vartheta}$ is a P^n-supermartingale.
Define now processes $y^{n,\vartheta}$, $m^{n,\vartheta}$, and $h^{n,\vartheta}$ on the predictable interval $\Gamma^{n,\vartheta} := \{Z^{n,\vartheta}_- > 0\}$ by:

$$y^{n,\vartheta} := (1/Y^{n,\vartheta}_-) \cdot Y^{n,\vartheta},$$

Some extra notation. 2

$m^{n,\vartheta}$ and $h^{n,\vartheta}$ are a local martingale and a predictable increasing process respectively in the Doob–Meyer decomposition

$$y^{n,\vartheta} = m^{n,\vartheta} - h^{n,\vartheta}$$

of a local supermartingale $y^{n,\vartheta}$. The process $m^{n,\vartheta}$ is, in fact, a P^n-locally square-integrable martingale on $\Gamma^{n,\vartheta}$, and $h^{n,\vartheta}$ is the Hellinger processes $h(\frac{1}{2}; P^n, P^{n,\vartheta})$ of order $1/2$ for P^n and $P^{n,\vartheta}$.

Assumptions on convergence. 1

In the theorem below we assume also that

- For every n there is given a locally square-integrable martingale $B^n = (B^{n,j})_{j \leqslant q}$, $B^n_0 = 0$, on $(\Omega^n, \mathscr{F}^n, \mathbb{F}^n, P^n)$ with values in $\mathbb{R}^q$.
-
$$\langle B^n, B^n \rangle_t - C_t \circ B^n \xrightarrow{\mathrm{P}^n} 0, \quad n \to \infty, \quad \text{for all} \quad t \in S,$$

  where S is a dense subset of $[0, 1]$ containing 0 and 1.
-
$$\|x\|^2 1_{\{\|x\| > \varepsilon\}} \star \nu_1^{B^n} \xrightarrow{\mathrm{P}^n} 0, \quad n \to \infty, \quad \text{for all } \varepsilon > 0,$$

Assumptions on convergence. 2

- Let $K^n := G^n \circ B^n$ and $M^n := K^n_- \cdot B^n$. Then

$$\left\langle m^{n,\vartheta_n} - \frac{1}{2}\vartheta_n^\top M^n \right\rangle_1 \xrightarrow{\mathsf{P}^n} 0, \quad n \to \infty,$$

for each bounded sequence $\{\vartheta_n\}$.

Main result

Theorem

Let all the above assumptions be satisfied. Then, as $n \to \infty$,

$$\mathscr{L}(M^n, \langle M^n \rangle | \mathsf{P}^n) \longrightarrow \mathscr{L}(M, \langle M \rangle | \mathsf{P}), \quad \textit{in } \mathbb{D}([0,1], \mathbb{R}^k),$$

$$(P^n) \lhd (P^{n,\vartheta_n}),$$

and

$$\sup_{t \leqslant 1} \left| \log Z_t^{n,\vartheta_n} - \left(\vartheta_n^\top M_t^n - \frac{1}{2} \vartheta_n^\top \langle M^n \rangle_t \vartheta_n^\top \right) \right| \xrightarrow{\mathsf{P}^n} 0,$$

for each bounded sequence $\{\vartheta_n\}$.

Additional remarks

If G is a Gaussian process on $(\Omega, \mathscr{F}, P)$, then

$$E \exp\Big(\vartheta^\top M_1 - \frac{1}{2}\vartheta^\top \langle M\rangle_1 \vartheta\Big) = 1$$

for any $\vartheta \in \mathbb{R}^k$ and

$$(P^n) \lhd \rhd (P^{n,\vartheta_n})$$

for each bounded sequence $\{\vartheta_n\}$. In particular, this is true if B is a Gaussian martingale (equivalently, C is deterministic) and G is a linear transformation on the corresponding set of continuous functions.
If, additionally, the matrix $\langle M\rangle_t$ is P-a.s. nonsingular, then the family $P_t^{n,\vartheta}$ is locally asymptotically quadratic (LAQ) at ϑ_0.

Outline

AR(p) model

Let us consider an autoregressive AR(p) model

$$y_n = \vartheta_1 y_{n-1} + \cdots + \vartheta_p y_{n-p} + \varepsilon_n,$$

where $\boldsymbol{\vartheta} = (\vartheta_1, \ldots, \vartheta_p)^\top$ is an unknown parameter, ε_n are i.i.d. random variables with $\mathrm{E}\varepsilon_n = 0$ and $\mathrm{E}\varepsilon_n^2 = 1$. We also assume that ε_n have a Lebesgue density $f(x)$ with a finite Fisher information $\boldsymbol{I}$. More precisely, there is a function $v(x)$ (the score function) such that

$$\boldsymbol{I} := \int v^2(x) f(x)\, dx < \infty$$

and

$$\int \Big(\sqrt{f(x-u)} - \sqrt{f(x)} - \frac{1}{2} v(x) \sqrt{f(x)} \Big)^2 dx \to 0, \quad , u \to 0.$$

Multiple unit root

Note that

$$\int xv(x)f(x)\,dx = 1 \quad \text{and} \quad \boldsymbol{I} \geqslant 1.$$

Let

$$\phi(z) = \phi(z;\boldsymbol{\vartheta}) := 1 - \vartheta_1 z - \cdots - \vartheta_p z^p.$$

We assume that the true value $\boldsymbol{\vartheta}_0$ of the parameter is such that

$$\phi(z;\boldsymbol{\vartheta}_0) = (1 - z)^p.$$

Prerequisites for asymptotic analysis. 1

Put

$$\boldsymbol{y}_n = (y_n, y_{n-1}, \dots, y_{n-p+1})^\top.$$

Let $\mathbb{B}$ be the backshift operator. We assume that ϑ_0 is a true value of the parameter. Then

$$(1-\mathbb{B})^p y_n = \varepsilon_n.$$

Put

$$y_n(j) = (1-\mathbb{B})^{p-j} y_n, \quad j = 0, \dots, p,$$

$$U_n = \big(y_n(p), \dots, y_n(1)\big)^\top.$$

Prerequisites for asymptotic analysis. 2

The introduced objects are connected by

$$M\boldsymbol{y}_n = U_n,$$

where

$$M := \begin{pmatrix} 1 & 0 & \dots\dots\dots\dots\dots\dots & & 0 \\ 1 & -1 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 1 & -\binom{p-1}{1} & \dots & (-1)^{p-2}\binom{p-1}{p-2} & (-1)^{p-1} \end{pmatrix},$$

and

$$y_n(j-1) = (1-\mathbb{B})y_n(j) = y_n(j) - y_{n-1}(j),$$

hence

$$y_n(j) = \sum_{k=1}^{n} y_k(j-1), \quad j = 1, \dots, p.$$

Normalizing matrix

Take

$$J_n := \begin{pmatrix} n^{-p} & 0 & \dots & 0 \\ 0 & n^{1-p} & \dots & 0 \\ \hdotsfor{4} \\ 0 & 0 & \dots & n^{-1} \end{pmatrix} M, \quad \varphi_n := J_n^\top.$$

Here

$$Z_t^{n,\boldsymbol{\vartheta}} = \frac{d\mathrm{P}_{[nt]}^{n,\boldsymbol{\vartheta}_0+\varphi_n\boldsymbol{\vartheta}}}{d\mathrm{P}_{[nt]}^{n,\boldsymbol{\vartheta}_0}}.$$

Approximation for the likelihood

It can be shown that

$$\sup_{t\leqslant 1}\left|\log Z_t^{n,\vartheta_n}-\left(\vartheta_n^\top M_t^n-\frac{1}{2}\vartheta_n^\top\langle M^n\rangle_t\vartheta_n^\top\right)\right|\xrightarrow{\mathsf{P}^n}0,$$

where

$$\begin{aligned}M_t^n&=J_n\sum_{k=1}^{[nt]}\boldsymbol{y}_{k-1}v(\varepsilon_n)\\&=\sum_{k=1}^{[nt]}n^{1/2-j}U_{k-1}(j)\frac{v(\varepsilon_k)}{n^{1/2}}.\end{aligned}$$

Construction of B^n, B.

This suggests to take $q = 2$,

$$B^n(1) = \sum_{k=1}^{[nt]} \frac{v(\varepsilon_k)}{n^{1/2}}, \quad B^n(2) = \sum_{k=1}^{[nt]} \frac{\varepsilon_k}{n^{1/2}},$$

which converges to a two-dimensional Gaussian martingale $B = (B(1), B(2))^\top$ with the quadratic characteristic

$$\langle B \rangle_t = \begin{pmatrix} \boldsymbol{I} & 1 \\ 1 & 1 \end{pmatrix} t.$$

Construction of G^n, G.

Next, put for

$$G^n(i,2) \equiv 0, \quad i = 1, \dots, p,$$

$$H^n(\alpha) = \int_0^t \alpha\Big(\frac{[ns]}{n}\Big)\, ds,$$

$$G^n(1,1)(\alpha) = \alpha,$$

$$G^n(i,1) = H^n \circ G^n(i,1), \quad i = 2, \dots, p.$$

Then

$$M^n = K^n_- \cdot B^n,$$

The limiting process

thus

$$M = \Big(M(i),\ i = p, p-1, \dots, 1\Big)$$

with

$$M(i)_t = \int_0^t F(i)_s\, dB(1)_s, \quad i = 1, \dots, p,$$

$$F(1) = B(2),$$

$$F(i)_t = \int_0^t F(i-1)_s\, ds, \quad i = 2, \dots, p.$$

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