A

Mandelbrot–van Ness Representation: Some Related Calculations

Now we calculate the constant that appeared in the Mandelbrot–van Ness representation of fBm (see Section 1.3, Theorem 1.3.1).

Lemma A.0.1. *The following equalities hold:*

$$C_H^{(2)} := \left(\int_{\mathbb{R}_+} ((1+s)^\alpha - s^\alpha)^2 ds + \frac{1}{2H} \right)^{-1} = \frac{(2H \sin \pi H \Gamma(2H))^{1/2}}{\Gamma(1+\alpha)}.$$

Proof. Recall that the constant $C_H^{(2)}$ is chosen to normalize the fBm

$$\overline{B}_t^H = C_H^{(2)} \int_{\mathbb{R}} k_H(t,u) dW_u = C_H^{(2)} \Gamma(1+\alpha) \int_{\mathbb{R}} (I_-^\alpha \mathbf{1}_{(0,t)})(x) dW_x$$

(see Lemma 1.1.3). Therefore, the first equality is evident, since

$$\int_{\mathbb{R}} (k_H(t,u))^2 du = \int_{-\infty}^0 ((t-x)^\alpha - (-x)^\alpha)^2 dx + \int_0^t (t-x)^{2\alpha} dx$$
$$= t^{2H} \left(\int_0^\infty ((1+s)^\alpha - s^\alpha)^2 ds + \frac{1}{2H} \right).$$

We obtain the second equality if we note that

$$\int_{\mathbb{R}} (I_-^\alpha \mathbf{1}_{(0,t)})(x)^2 dx = \frac{1}{2\pi} \int_{\mathbb{R}} \left(\widehat{\mathcal{F}}(I_-^\alpha \mathbf{1}_{(0,t)})(x) \right)^2 dx$$

and according to Theorem 1.1.5

$$\widehat{\mathcal{F}}(I_-^\alpha \mathbf{1}_{(0,t)})(x)(\lambda) = \widehat{1_{(0,t)}}(\lambda) |\lambda|^{-\alpha} \exp\left\{ \frac{\alpha \pi i}{2} \operatorname{sign} \lambda \right\}$$
$$= \frac{e^{it\lambda} - 1}{i\lambda} |\lambda|^{-\alpha} \exp\left\{ \frac{\alpha \pi i}{2} \operatorname{sign} \lambda \right\}.$$

Therefore,

$$\int_{\mathbb{R}} (I_-^\alpha \mathbf{1}_{(0,t)})(x)^2 dx = \frac{1}{2\pi}\int_{\mathbb{R}} |e^{it\lambda}-1|^2 |\lambda|^{-2\alpha-2} d\lambda$$

$$= \frac{1}{2\pi}\int_{\mathbb{R}} (1-\cos t\lambda)^2 |\lambda|^{-2\alpha-2} d\lambda + \frac{1}{2\pi}\int_{\mathbb{R}} \sin^2 t\lambda |\lambda|^{-2\alpha-2} d\lambda$$

$$= \frac{1}{\pi}\int_0^\infty \frac{(1-\cos t\lambda)^2}{\lambda^{2\alpha+2}} d\lambda + \frac{1}{\pi}\int_0^\infty \frac{\sin^2 t\lambda}{\lambda^{2\alpha+2}} d\lambda$$

$$= t^{2H}\left(\frac{1}{\pi}\int_0^\infty \frac{(1-\cos \lambda)^2}{\lambda^{2\alpha+2}} d\lambda + \frac{1}{\pi}\int_0^\infty \frac{\sin^2 \lambda}{\lambda^{2\alpha+2}} d\lambda\right) = \frac{t^{2H}}{2H \sin \pi H \Gamma(2H)},$$

whence the proof follows. □

B

Approximation of Beta Integrals and Estimation of Kernels

These results were obtained by E.Valkeila (KMV05).

Lemma B.0.1. *Assume that* $-1 < \delta < 0$, $\beta > -1$ *and* $n \geq 2$. *Then for* $\beta \geq 0$

$$|I(\delta,\beta) - I_n(\delta,\beta)| \leq C_1(\delta,\beta) n^{-\alpha-1}, \tag{B.0.1}$$

and with $-1 < \beta < 0$ *we have*

$$|I(\alpha,\beta) - I_n(\delta,\beta)| \leq C_2(\delta,\beta) n^{-\alpha-\beta-1} \tag{B.0.2}$$

(for the value of the constants, see the proof).

Proof. We start the proof with

$$\begin{aligned} I(\delta,\beta) - I_n(\delta,\beta) &= \int_0^{\frac{1}{n}} s^\delta (1-s)^\beta ds - n^{-\delta-1} \\ &+ \sum_{k=1}^{n-2} \int_{\frac{k}{n}}^{\frac{k+1}{n}} \left(s^\delta (1-s)^\beta - \left(\frac{k+1}{n}\right)^\delta \left(1 - \frac{k}{n}\right)^\beta \right) ds \\ &+ \int_{1-\frac{1}{n}}^1 s^\delta (1-s)^\beta ds - n^{-\beta-1}. \end{aligned}$$

We work first with the integral on $(0, 1/n)$. We have

$$\begin{aligned} \int_0^{\frac{1}{n}} s^\delta (1-s)^\beta ds - n^{-\delta-1} &= \int_0^{\frac{1}{n}} \left(s^\delta - n^{-\delta}\right) ds \\ &+ \int_0^{\frac{1}{n}} s^\delta \left((1-s)^\beta - 1\right) ds; \end{aligned} \tag{B.0.3}$$

here

$$0 \leq \int_0^{\frac{1}{n}} \left(s^\delta - n^{-\delta}\right) ds = -\delta/(\delta+1) n^{-\delta-1},$$

if $\beta \geq 0$, then

$$| \int_0^{\frac{1}{n}} s^\delta \left((1-s)^\beta - 1 \right) ds| \leq \int_0^{\frac{1}{n}} s^\delta ds$$

and if $\beta < 0$ and $s \leq 1/n$, then $0 \leq (1-s)^\beta - 1 \leq 2^{-\beta} - 1$. Use these estimates in (B.0.3) to obtain

$$| \int_0^{\frac{1}{n}} s^\delta (1-s)^\beta ds - n^{-\delta-1}| \leq C_1(\delta, \beta) n^{-\delta-1}. \tag{B.0.4}$$

Next, we work with the integral on $(1-1/n, 1)$. We have

$$\int_{1-\frac{1}{n}}^1 s^\delta (1-s)^\beta ds - n^{-\beta-1} = \int_{1-\frac{1}{n}}^1 \left((1-s)^\beta - n^{-\beta} \right) ds$$
$$+ \int_{1-\frac{1}{n}}^1 (1-s)^\beta \left(s^\delta - 1 \right) ds,$$

and this gives

$$\Big| \int_{1-\frac{1}{n}}^1 s^\delta (1-s)^\beta ds - n^{-\beta-1} \Big| \leq \frac{|\beta|}{1+\beta} n^{-\beta-1} + 2^{-\delta} n^{-\beta-1}. \tag{B.0.5}$$

We continue with the middle term. We have

$$\sum_{k=1}^{n-2} \left(\int_{\frac{k}{n}}^{\frac{k+1}{n}} s^\delta (1-s)^\beta ds - \left(\frac{k+1}{n} \right)^\delta \left(1 - \frac{k}{n} \right)^\beta \frac{1}{n} \right)$$
$$= \sum_{k=1}^{n-2} \left(\int_{\frac{k}{n}}^{\frac{k+1}{n}} \left(s^\delta - \left(\frac{k+1}{n} \right)^\delta \right) (1-s)^\beta ds \right)$$
$$+ \sum_{k=1}^{n-2} \left(\int_{\frac{k}{n}}^{\frac{k+1}{n}} \left(\frac{k+1}{n} \right)^\delta \left((1-s)^\beta - \left(1 - \frac{k}{n} \right)^\beta \right) ds \right). \tag{B.0.6}$$

The first term on the right-hand side of (B.0.6) is always positive, when $\delta < 0$. We use the estimate

$$s^\delta - ((k+1)/n)^\delta \leq (k/n)^\delta - ((k+1)/n)^\delta.$$

If $\beta \geq 0$, then $(1-s)^\beta \leq 1$ and so for the first term on the right-hand side of (B.0.6) we obtain

$$0 \leq \sum_{k=1}^{n-2} \left(\int_{k/n}^{(k+1)/n} \left(s^\delta - ((k+1)/n)^\delta \right) (1-s)^\beta ds \right)$$

$$\leq n^{-\delta-1}\sum_{k=1}^{n-2}\left(k^{\delta}-(k+1)^{\delta}\right)\leq n^{-\delta-1}. \tag{B.0.7}$$

If $\beta \leq 0$ then

$$\int_{k/n}^{(k+1)/n}\left(s^{\delta}-((k+1)/n)^{\delta}\right)(1-s)^{\beta}\,ds \leq \frac{1}{1+\beta}n^{-\delta-\beta-1}\Big(k^{\delta}$$

$$-(k+1)^{\delta}\Big)\left((n-k)^{\beta+1}-(n-(k+1))^{\beta+1}\right)\leq n^{-\delta-\beta-1}\left(k^{\delta}-(k+1)^{\delta}\right),$$

and this gives the estimate

$$0\leq\sum_{k=1}^{n-2}\left(\int_{k/n}^{(k+1)/n}\left(s^{\alpha}-((k+1)/n)^{\alpha}\right)(1-s)^{\beta}\,ds\right)\leq n^{-\alpha-\beta-1}. \tag{B.0.8}$$

Finally, the second part of the middle term is

$$J_n:=\sum_{k=1}^{n-2}\left(\int_{k/n}^{(k+1)/n}((k+1)/n)^{\delta}\left((1-s)^{\beta}-(1-k/n)^{\beta}\right)ds\right).$$

If $\beta \geq 0$, then with calculations similar to above

$$|J_n|\leq n^{-\delta-1}, \tag{B.0.9}$$

and if $\beta < 0$, then

$$|J_n|\leq -\frac{1}{\beta}2^{\beta}n^{-\alpha-\beta-1}. \tag{B.0.10}$$

Combining the bounds (B.0.3)–(B.0.7) and (B.0.9) we get $C_1(\delta,\beta)$, and combining the bounds (B.0.3)–(B.0.6), (B.0.8) and (B.0.10) we get $C_2(\delta,\beta)$. □

Lemma B.0.2. *Put*

$$H_n:=\sum_{k=0}^{n-1}\Bigg(\left(\frac{k+1}{n}\right)^{1/4-H}\left(1-\frac{k}{n}\right)^{3/4-H}\left(\left(\frac{k+1}{n}\right)^{2H}-\left(\frac{k}{n}\right)^{2H}\right)$$

$$-2H\left(\frac{k+1}{n}\right)^{H-3/4}\left(1-\frac{k}{n}\right)^{3/4-H}\frac{1}{n}\Bigg).$$

Then

$$|H_n|\leq Cn^{-\min(1,\frac{1}{4}+H)}. \tag{B.0.11}$$

Proof. The proof of Lemma B.0.2 is similar to Lemma B.0.1. □

The proof of the following lemma is obvious.

Lemma B.0.3. *Consider the expression*

$$\bar{u}_n(H) := \frac{1}{n} \sum_{k=0}^{n-1} \left(\left(\frac{k+1}{n} \right)^{2H} - \left(\frac{k}{n} \right)^{2H} \right)^2 .$$

Then

$$|\bar{u}_n(H)| \leq \frac{C}{n^2}. \tag{B.0.12}$$

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