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# Modulus of continuity of some conditionally sub-Gaussian fields, application to stable random fields

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## Abstract

In this paper we study modulus of continuity and rate of convergence of series of conditionally sub-Gaussian random fields. This framework includes both classical series representations of Gaussian fields and LePage series representations of stable fields. We enlighten their anisotropic properties by using an adapted quasi-metric instead of the classical Euclidean norm. We specify our assumptions in the case of shot noise series where arrival times of a Poisson process are involved. This allows us to state unified results for harmonizable (multi)operator scaling stable random fields through their LePage series representation, as well as to study sample path properties of their multistable analogues.

*Keywords:* sub-Gaussian, stable and multistable random fields, operator scaling property, Hölder regularity.

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## 1. Introduction

In recent years, lots of new random fields have been defined to propose new models for rough real data. To cite a few of them let us mention the (multi)fractional Brownian fields (see e.g. [Benassi et al. \(1997\)](#)), the linear and harmonizable (multi)fractional stable processes [Stoev and Taqqu \(2004\)](#); [Dozzi and Shevchenko \(2011\)](#) and some anisotropic fields such as the (multi)fractional Brownian and stable sheets [Ayache and Leger \(2000\)](#); [Ayache et al. \(2009\)](#) and the (multi)operator scaling Gaussian and stable fields [Biermé et al. \(2007, 2011\)](#). In the Gaussian setting, sample path regularity relies on mean square

regularity. To study finer properties such as modulus of continuity, a powerful technique consists in considering a representation of the field as a series of random fields, using for instance Karhunen Loeve decomposition (see Adler (1981) Chapter 3), Fourier or wavelet series (as in Kahane (1960); Ayache and Xiao (2005)). This also allows generalizations to non-Gaussian framework using for instance LePage series LePage (1989, 1981) for stable distributions (see e.g. Kôno and Maejima (1991a)). Actually, following previous works of LePage LePage (1981) and Marcus and Pisier Marcus and Pisier (1984), Kôno and Maejima proved in Kôno and Maejima (1991b) that, for  $\alpha \in (0, 2)$ , an isotropic complex-valued  $\alpha$ -stable random variable may be represented as a convergent shot noise series of the form

$$\sum_{n=1}^{+\infty} T_n^{-1/\alpha} X_n, \quad (1)$$

with  $(T_n)_{n \geq 1}$  the sequence of arrival times of a Poisson process of intensity 1, and  $(X_n)_{n \geq 1}$  a sequence of independent identically distributed (i.i.d.) isotropic complex-valued random variables, which is assumed to be independent of  $(T_n)_{n \geq 1}$  and such that  $\mathbb{E}(|X_1|^\alpha) < +\infty$ . When  $X_n = V_n g_n$  with  $(g_n)_{n \geq 1}$  a sequence of i.i.d. Gaussian random variables independent of  $(V_n, T_n)_{n \geq 1}$ , the series may be considered as a conditional Gaussian series. This is one of the main argument used in Kôno and Maejima (1991a); Dozzi and Shevchenko (2011); Biermé and Lacaux (2009); Biermé et al. (2011) to study the sample path regularity of some stable random fields. Another classical representation consists in choosing  $X_n = V_n \varepsilon_n$  with  $(\varepsilon_n)_{n \geq 1}$  a sequence of i.i.d. Rademacher random variables i.e. such that  $\mathbb{P}(\varepsilon_n = 1) = \mathbb{P}(\varepsilon_n = -1) = 1/2$ . Both  $g_n$  and  $\varepsilon_n$  are sub-Gaussian random variables. Sub-Gaussian random variables have first been introduced in Kahane (1960) for the study of random Fourier series. Their main property is that their tail distributions behave like the Gaussian ones and then sample path properties of sub-Gaussian fields may be set as for Gaussian ones (see Theorem 12.16 of Ledoux and Talagrand (1991) for instance). In particular they also rely on their mean square regularity.

In this paper we study the sample path regularity of the complex-valued series of conditionally sub-Gaussian fields defined as

$$S(x) = \sum_{n=1}^{+\infty} W_n(x) g_n, \text{ for } x \in K_d \subset \mathbb{R}^d, \quad (2)$$

with  $(g_n)_{n \geq 1}$  a sequence of independent symmetric sub-Gaussian complex random variables, which is assumed independent of  $(W_n)_{n \geq 1}$ . In this setting we give sufficient assumptions on the sequence  $(W_n)_{n \geq 1}$  to get an upper bound of the modulus of continuity of  $S$  as well as a uniform rate of convergence. Then, we focus on shot noises series

$$S(\alpha, u) = \sum_{n=1}^{+\infty} T_n^{-1/\alpha} V_n(\alpha, u) g_n, \text{ } x = (\alpha, u) \in K_{d+1} \subset (0, 2) \times \mathbb{R}^d,$$

with  $(T_n)_{n \geq 1}$  the sequence of arrival times of a Poisson process. Assuming the independence of  $(T_n)_{n \geq 1}$ ,  $(V_n)_{n \geq 1}$  and  $(g_n)_{n \geq 1}$ , we state some more convenient conditions based

on moments of  $V_n$  to ensure that the main assumptions of this paper are fulfilled. In particular when  $V_n(\alpha, u) := X_n$  is a symmetric random variable, one of our main result gives a uniform rate of convergence of the shot noise series (1) in  $\alpha$  on any compact  $K_1 = [a, b] \subset (0, 2)$ , which improves the results obtained in [Cohen et al. \(2008\)](#) on the convergence of such series. In the framework of LePage random series, which are particular examples of shot noise series, we also establish that to improve the upper bound of the modulus of continuity of  $S$ , one has the opportunity to use an other series representation of  $S$ . On the one hand, our framework allows to include in a general setting some sample path regularity results already obtained in [Biermé and Lacaux \(2009\)](#); [Biermé et al. \(2011\)](#) for harmonizable (multi)-operator scaling stable random fields. On the other hand, considering  $\alpha$  as a function of  $u \in \mathbb{R}^d$ , we also investigate sample path properties of multistable random fields that have been introduced in [Falconer and Lévy Véhel \(2009\)](#). To illustrate our results, we focus on harmonizable random fields.

The paper falls into the following parts. In Section 2 we recall definition and properties of sub-Gaussian random variables and state our first assumption needed to ensure that the random field  $S$  is well-defined by (2). We also introduce a notion of anisotropic local regularity, which is obtained by replacing the isotropic Euclidean norm of  $\mathbb{R}^d$  by a quasi-metric that can reveal the anisotropy of the random fields. Section 3 is devoted to our main results concerning both local modulus of continuity of the random field  $S$  defined by the series (2) and rate of convergence of this series. Section 4 deals with the particular setting of shot noise series, the case of LePage series being treated in Subsection 4.3. Then Section 5 is devoted to the study of the sample path regularity of stable or even multistable random fields. Technical proofs are postponed to Appendix for reader convenience.

## 2. Preliminaries

### 2.1. Sub-Gaussian random variables

Real-valued sub-Gaussian random variables have been defined by [Kahane \(1960\)](#). The structure of the class of these random variables and some conditions for continuity of real-valued sub-Gaussian random fields have been studied in [Buldygin and Kozačenko \(1980\)](#). In this paper we focus on conditionally complex-valued sub-Gaussian random fields, where a complex sub-Gaussian random variable is defined as follows.

**Definition 2.1.** *A complex-valued random variable  $Z$  is sub-Gaussian if there exists  $s \in [0, +\infty)$  such that*

$$\forall z \in \mathbb{C}, \mathbb{E} \left( e^{\Re(\bar{z}Z)} \right) \leq e^{\frac{s^2 |z|^2}{2}}. \quad (3)$$

**Remark 2.1.** *This definition coincides also with complex sub-Gaussian random variables as defined in [Fukuda \(1990\)](#) in the more general setting of random variables with values in a Banach space. Moreover, for a real-valued random variable  $Z$ , it also coincides*

with the definition in [Kahane \(1960\)](#). [Kahane \(1960\)](#) called the smallest  $s$  such that (3) holds the Gaussian shift of the sub-Gaussian variable  $Z$ . In this paper, if (3) is fulfilled, we say that  $Z$  is sub-Gaussian with parameter  $s$ .

**Remark 2.2.** A complex-valued random variable  $Z$  is sub-Gaussian if and only if  $\Re(Z)$  and  $\Im(Z)$  are real sub-Gaussian random variables. Note that if  $Z$  is sub-Gaussian with parameter  $s$  then  $\mathbb{E}(\Re(Z)) = \mathbb{E}(\Im(Z)) = 0$  and  $\mathbb{E}(\Re(Z)^2) \leq s^2$  as well as  $\mathbb{E}(\Im(Z)^2) \leq s^2$ .

The main property of sub-Gaussian random variables is that their tail distributions decrease exponentially as the Gaussian ones (see Lemma A.1). Moreover, considering convergent series of independent symmetric sub-Gaussian random variables, a uniform rate of decrease is available and the limit remains a sub-Gaussian random variable. This result, stated below, is one of the main tool we use to study sample path properties of conditionally sub-Gaussian random fields.

**Proposition 2.1.** Let  $(g_n)_{n \geq 1}$  be a sequence of independent symmetric sub-Gaussian random variables with parameter  $s = 1$ . Let us consider a complex-valued sequence  $a = (a_n)_{n \geq 1}$  such that

$$\|a\|_{\ell^2}^2 = \sum_{n=1}^{+\infty} |a_n|^2 < +\infty.$$

1. Then, for any  $t \in (0, +\infty)$ ,  $\mathbb{P}\left(\sup_{N \in \mathbb{N} \setminus \{0\}} \left| \sum_{n=1}^N a_n g_n \right| > t \|a\|_{\ell^2}\right) \leq 8e^{-\frac{t^2}{8}}.$
2. Moreover, the series  $\sum a_n g_n$  converges almost surely, and its limit  $\sum_{n=1}^{+\infty} a_n g_n$  is a sub-Gaussian random variable with parameter  $\|a\|_{\ell^2}.$

**Proof.** See Appendix, Section A. □

**Remark 2.3.** In the previous proposition, assuming that the parameter  $s = 1$  is not restrictive since  $a_n$  can be replaced by  $a_n s_n$  and  $g_n$  by  $g_n/s_n$  when  $g_n$  is sub-Gaussian with parameter  $s_n > 0$ .

## 2.2. Conditionally sub-Gaussian series

In the whole paper, for  $d \geq 1$ ,  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$  is a compact  $d$ -dimensional interval and for each integer  $N \in \mathbb{N}$ , we consider

$$S_N(x) = \sum_{n=1}^N W_n(x) g_n, \quad x \in K_d \tag{4}$$

where  $\sum_{n=1}^0 = 0$  by convention and where the sequence  $(W_n, g_n)_{n \geq 1}$  satisfies the following assumption.

**Assumption 1.** Let  $(g_n)_{n \geq 1}$  and  $(W_n)_{n \geq 1}$  be independent sequences of random variables.

1.  $(g_n)_{n \geq 1}$  is a sequence of independent symmetric complex-valued sub-Gaussian random variables with parameter  $s = 1$ .
2.  $(W_n)_{n \geq 1}$  is a sequence of complex-valued continuous random fields defined on  $K_d$  and such that

$$\forall x \in K_d, \quad \text{almost surely} \quad \sum_{n=1}^{+\infty} |W_n(x)|^2 < +\infty.$$

Under Assumption 1, conditionally on  $(W_n)_{n \geq 1}$ , each  $S_N$  is a sub-Gaussian random field defined on  $K_d$ . Moreover, for each  $x$ , Proposition 2.1 and Fubini Theorem lead to the almost sure convergence of  $S_N(x)$  as  $N \rightarrow +\infty$ . The limit field  $S$  defined by

$$S(x) = \sum_{n=1}^{+\infty} W_n(x) g_n, \quad x \in K_d \subset \mathbb{R}^d, \quad (5)$$

is then a conditionally sub-Gaussian random field. In the sequel, we study almost sure uniform convergence and rate of uniform convergence of  $(S_N)_{N \in \mathbb{N}}$  as well as the sample path properties of  $S$ .

Assume first that each  $g_n$  is a Gaussian random variable and that each  $W_n$  is a deterministic random field, which implies that  $S$  is a Gaussian centered random field. Then, it is well-known that its sample path properties are given by the behavior of

$$s(x, y) := \left( \sum_{n=1}^{+\infty} |W_n(x) - W_n(y)|^2 \right)^{1/2}, \quad x, y \in K_d, \quad (6)$$

since  $s^2$  is proportional to the variogram  $(x, y) \mapsto v(x, y) := \mathbb{E}[|S(x) - S(y)|^2]$ . In the following, we see that under Assumption 1, the behavior of  $S$  is still linked with the behavior of the parameter  $s$ . In this more general framework, a key tool is to remark that conditionally on  $(W_n)_{n \geq 1}$ ,  $S$  is a sub-Gaussian random field and the random variable  $S(x) - S(y)$  is sub-Gaussian with parameter  $s(x, y)$ .

We are particularly interested in anisotropic random fields  $S$  (and then anisotropic parameters  $s$ ). Therefore, next section deals with an anisotropic generalization of the classical Hölder regularity, that is with a notion of regularity which takes into account the anisotropy of the fields under study.

### 2.3. Anisotropic local regularity

Let us first recall the notion of quasi-metric (see e.g. [Paluszyński and Stempak \(2009\)](#)), which is more adapted to our framework.

**Definition 2.2.** A continuous function  $\rho : \mathbb{R}^d \times \mathbb{R}^d \rightarrow [0, +\infty)$  is called a *quasi-metric* on  $\mathbb{R}^d$  if

1.  $\rho$  is faithful i.e.  $\rho(x, y) = 0$  iff  $x = y$ ;
2.  $\rho$  is symmetric i.e.  $\rho(x, y) = \rho(y, x)$ ;
3.  $\rho$  satisfies a quasi-triangle inequality: there exists a constant  $\kappa \geq 1$  such that

$$\forall x, y, z \in \mathbb{R}^d, \rho(x, z) \leq \kappa (\rho(x, y) + \rho(y, z)).$$

Observe that a continuous function  $\rho$  is a metric on  $\mathbb{R}^d$  if and only if  $\rho$  is a quasi-metric on  $\mathbb{R}^d$  which satisfies Assertion 3. with  $\kappa = 1$ . In particular, the Euclidean distance is an isotropic quasi-metric and its following anisotropic generalization

$$(x, y) \mapsto \rho(x, y) := \left( \sum_{i=1}^d |x_i - y_i|^{p/a_i} \right)^{1/p} \quad \text{where } p > 0 \text{ and } a_1, \dots, a_d > 0,$$

is also a quasi-metric. Such quasi-metrics are particular cases of the following general example.

**Example 2.1.** Let us consider  $E$  a real  $d \times d$  matrix whose eigenvalues have positive real parts and  $\tau_E : \mathbb{R}^d \rightarrow \mathbb{R}^+$  a continuous even function such that

- i) for all  $x \neq 0$ ,  $\tau_E(x) > 0$ ;
- ii) for all  $r > 0$  and all  $x \in \mathbb{R}^d$ ,  $\tau_E(r^E x) = r \tau_E(x)$  with  $r^E = \exp((\ln r)E)$ .

The classical example of such a function is the radial part of polar coordinates with respect to  $E$  introduced in Chapter 6 of [Meerschaert and Scheffler \(2001\)](#). Other examples have been given in [Biermé et al. \(2007\)](#).

Let us consider the continuous function  $\rho_E$ , defined on  $\mathbb{R}^d \times \mathbb{R}^d$  by

$$\rho_E(x, y) = \tau_E(x - y).$$

Then, by definition of  $\tau_E$ ,  $\rho_E$  is faithful and symmetric. Moreover, by Lemma 2.2 of [Biermé et al. \(2007\)](#),  $\rho_E$  also satisfies a quasi-triangle inequality. Hence,  $\rho_E$  is a quasi-metric on  $\mathbb{R}^d$  and it is adapted to study operator scaling random fields (see [Biermé et al. \(2007\)](#); [Biermé and Lacaux \(2009\)](#) for example).

Let us remark that since  $\rho_E^\beta$  define a quasi-metric for  $E/\beta$  whatever  $\beta > 0$  is, we may restrict our study to matrix  $\bar{E}$  whose eigenvalues have real parts greater than one. Then, by Proposition 3.5 of [Biermé et al. \(2011\)](#), there exist  $0 < \underline{H} \leq \bar{H} \leq 1$  and two constants  $c_{2,1}, c_{2,2} \in (0, \infty)$  such that for all  $x, y \in \mathbb{R}^d$ ,

$$c_{2,1} \min(\|x - y\|^{\bar{H}}, \|x - y\|^{\underline{H}}) \leq \rho_E(x, y) \leq c_{2,2} \max(\|x - y\|^{\bar{H}}, \|x - y\|^{\underline{H}}),$$

where  $\|\cdot\|$  is the Euclidean norm on  $\mathbb{R}^d$ . In [Biermé et al. \(2011\)](#); [Biermé and Lacaux \(2009\)](#), this comparison is one of the main tool in the study of the regularity of some

stable anisotropic random fields. Therefore, throughout the paper, we consider a quasi-metric  $\rho$  such that there exist  $0 < \underline{H} \leq \overline{H} \leq 1$  and two constants  $c_{2,1}, c_{2,2} \in (0, \infty)$  such that for all  $x, y \in \mathbb{R}^d$ , with  $\|x - y\| \leq 1$ ,

$$c_{2,1}\|x - y\|^{\overline{H}} \leq \rho(x, y) \leq c_{2,2}\|x - y\|^{\underline{H}}. \quad (7)$$

Before we introduce the anisotropic regularity used in the following, let us briefly comment this assumption.

**Remark 2.4.**

1. The upper bound is needed in the sequel to construct a particular  $2^{-k}$  net for  $\rho$ , whose cardinality can be estimated using the lower bound.
2. Using the quasi-triangle inequality satisfied by  $\rho$  and its continuity, one deduces from (7) that for any non-empty compact set  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$ , there exist two finite positive constants  $c_{2,1}(K_d)$  and  $c_{2,2}(K_d)$  such that for all  $x, y \in K_d$ ,

$$c_{2,1}(K_d)\|x - y\|^{\overline{H}} \leq \rho(x, y) \leq c_{2,2}(K_d)\|x - y\|^{\underline{H}}. \quad (8)$$

3. It is not restrictive to assume that  $\overline{H} \leq 1$  since for any  $c > 0$ ,  $\rho^c$  is also a quasi-metric.

We will consider the following anisotropic local and uniform regularity property.

**Definition 2.3.** Let  $\beta \in (0, 1]$  and  $\eta \in \mathbb{R}$ . Let  $x_0 \in K_d$  with  $K_d \subset \mathbb{R}^d$ . A real-valued function  $f$  defined on  $K_d$  belongs to  $\mathcal{H}_{\rho, K_d}(x_0, \beta, \eta)$  if there exist  $\gamma \in (0, 1)$  and  $C \in (0, +\infty)$  such that

$$|f(x) - f(y)| \leq C \rho(x, y)^\beta |\log(\rho(x, y))|^\eta$$

for all  $x, y \in B(x_0, \gamma) \cap K_d = \{z \in K_d; \|z - x_0\| \leq \gamma\}$ . Moreover  $f$  belongs to  $\mathcal{H}_\rho(K_d, \beta, \eta)$  if there exists  $C \in (0, +\infty)$  such that

$$\forall x, y \in K_d, |f(x) - f(y)| \leq C \rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta.$$

**Remark 2.5.**

1. If  $f \in \mathcal{H}_{\rho, K_d}(x_0, \beta, \eta)$ , then  $f$  is continuous at  $x_0$ . Moreover, since  $h^\beta [\log(1 + h^{-1})]^\eta \sim_{h \rightarrow 0+} h^\beta |\log(h)|^\eta$  and since  $\rho$  satisfies Equation (7),  $f \in \mathcal{H}_{\rho, K_d}(x_0, \beta, \eta)$  if and only if for some  $\gamma > 0$ ,  $f \in \mathcal{H}_\rho(B(x_0, \gamma) \cap K_d, \beta, \eta)$ .
2. If  $f \in \mathcal{H}_\rho(K_d, \beta, \eta)$ , then  $f \in \mathcal{H}_{\rho, K_d}(x_0, \beta, \eta)$  for all  $x_0 \in K_d$ . The converse is also true since  $K_d$  is a compact. This follows from the Lebesgue's number lemma and the boundedness of the continuous function  $f$  on the compact set  $K_d$  (see Lemma B.2 stated in the appendix for an idea of the proof).



3. A function in  $\mathcal{H}_\rho(K_d, \beta, 0)$  may be view as a Lipschitz function on an homogeneous space [Macías and Segovia \(1979\)](#). Note also that when  $\rho$  is the Euclidean distance, for any  $\beta \leq 1$  and  $\eta \leq 0$ , the set  $\mathcal{H}_\rho(K_d, \beta, \eta)$  (respectively  $\mathcal{H}_{\rho, K_d}(x_0, \beta, \eta)$ ) is included in the set of Hölder functions of order  $\beta$  on  $K_d$  (respectively around  $x_0$ ).
4. Assuming  $\beta \leq 1$  is not restrictive since, for any  $c > 0$ ,  $\rho^c$  is also a quasi-metric.

The introduction of the logarithmic term appears naturally when considering Gaussian random fields. Actually, [Benassi et al. \(1997\)](#) proves that for all  $\beta \in (0, 1]$ , a large class of elliptic Gaussian random fields  $X_\beta$ , including the famous fractional Brownian fields, belongs a.s. to  $\mathcal{H}_{\rho, K_d}(x_0, \beta, 1/2)$  with  $\rho$  the Euclidean distance (see Theorem 1.3 in [Benassi et al. \(1997\)](#)). Moreover, Xiao [Xiao \(2010\)](#) also gives some anisotropic examples of Gaussian fields belonging a.s. to  $\mathcal{H}_{\rho, K_d}(x_0, 1, 1/2)$  for some anisotropic quasi-distance  $\rho = \rho_E$  associated with  $E$  a diagonal matrix (see Theorem 4.2 of [Xiao \(2009\)](#)). Finally, in [Biermé et al. \(2011\)](#), we construct stable and Gaussian random fields belonging a.s. to  $\mathcal{H}_{\rho_{x_0}, K_d}(x_0, 1 - \varepsilon, 0)$  for some convenient  $\rho_{x_0}$  (see Theorem 4.6 in [Biermé et al. \(2011\)](#)).

### 3. Main results on conditionally sub-Gaussian series

#### 3.1. Local modulus of continuity

In this section, we first give an upper bound of the local modulus of continuity of  $S$  defined by (4) under the following local assumption on the conditional parameter (6).

**Assumption 2.** Let  $x_0 \in K_d$  with  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$ . Let us consider  $\rho$  a quasi-metric on  $\mathbb{R}^d$  satisfying Equation (7). Assume that there exist an almost sure event  $\Omega'$  and some random variables  $\gamma > 0$ ,  $\beta \in (0, 1]$ ,  $\eta \in \mathbb{R}$  and  $C \in (0, +\infty)$  such that on  $\Omega'$

$$\forall x, y \in B(x_0, \gamma) \cap K_d, \quad s(x, y) \leq C \rho(x, y)^\beta |\log(\rho(x, y))|^\eta,$$

where we recall that the conditional parameter  $s$  is given by (6).

Note that the event  $\Omega'$ , the random variables  $\gamma, \beta, \eta$ ,  $C$  and the quasi-metric  $\rho$  may depend on  $x_0$ .

Let us now state the main result of this section on the modulus of continuity. The main difference with [Kôno and Maejima \(1991b\)](#); [Biermé and Lacaux \(2009\)](#); [Biermé et al. \(2011\)](#) is that we do not only consider the limit random field  $S$  but obtain a uniform upper bound in  $N$  for the modulus of continuity of  $S_N$ .

**Theorem 3.1.** Assume that Assumptions 1 and 2 are fulfilled. Then, almost surely, there exist  $\gamma^* \in (0, \gamma)$  and  $C \in (0, +\infty)$  such that for all  $x, y \in B(x_0, \gamma^*) \cap K_d$ ,

$$\sup_{N \in \mathbb{N}} |S_N(x) - S_N(y)| \leq C \rho(x, y)^\beta |\log \rho(x, y)|^{\eta+1/2}.$$

Moreover, almost surely  $(S_N)_{N \in \mathbb{N}}$  converges uniformly on  $B(x_0, \gamma^*) \cap K_d$  to  $S$  and the limit  $S$  belongs to  $\mathcal{H}_{\rho, K_d}(x_0, \beta, \eta + 1/2)$ . In particular, almost surely  $S$  is continuous at  $x_0$ .

**Proof.** See Appendix, Section B.1.  $\square$

Strengthening Assumption 2, the uniform convergence and the upper bound for the modulus of continuity are obtained on deterministic set. Next corollary is obtained using some covering argument.

**Corollary 3.2.** Assume that Assumptions 1 is fulfilled.

1. Assume that Assumption 2 holds for any  $x_0 \in K_d$  with the same almost sure event  $\Omega'$ , the same random variables  $\beta$  and  $\eta$ , and the same quasi-metric  $\rho$ . Then Theorem 3.1 holds replacing  $B(x_0, \gamma^*) \cap K_d$  by all the set  $K_d$  and almost surely  $S$  belongs to  $\mathcal{H}_{\rho}(K_d, \beta, \eta + 1/2)$ .
2. Assume now that Assumption 2 holds with a deterministic  $\gamma$ . Then Theorem 3.1 holds replacing  $B(x_0, \gamma^*) \cap K_d$  by  $B(x_0, \gamma) \cap K_d$  and almost surely  $S$  belongs to  $\mathcal{H}_{\rho}(B(x_0, \gamma) \cap K_d, \beta, \eta + 1/2)$ .

**Proof.** See Appendix, Section B.1.  $\square$

When considering  $S$  an operator scaling Gaussian random field, note that Li et al. (2013) proves that the upper bound obtained by Corollary 3.2 is optimal. Moreover for some Gaussian anisotropic random fields, Xiao (2009) also obtains a sample path regularity in the stronger  $L^p$ -sense on whole the compact  $K_d$ . This follows from an extension of the Garsia-Rodemich-Rumsey continuity lemma Garsia et al. (1970) or the minorization metric method of Kwapień and Ronsiński (2004). This would be interesting to study if these results still hold when considering a quasi-metric  $\rho$  (and not a metric) and if they can be applied to obtain the sample path regularity of  $S$  in the stronger  $L^p$ -sense on whole the compact  $K_d$ , strenghtening the assumption on the parameter  $s$ .

### 3.2. Rate of almost sure uniform convergence

This section is concerned with the rate of uniform convergence of the series  $(S_N)_{N \in \mathbb{N}}$  defined by (4). Under Assumption 1, this series converges to  $S$  and, for any integer  $N$ , we consider the rest

$$R_N(x) = S(x) - S_N(x) = \sum_{n=N+1}^{+\infty} W_n(x)g_n, \quad x \in K_d \subset \mathbb{R}^d.$$

Then, conditionally on  $(W_n)_{n \geq 1}$ ,  $R_N(x) - R_N(y)$  is a sub-Gaussian random variable with parameter

$$r_N(x, y) = \left( \sum_{n=N+1}^{+\infty} |W_n(x) - W_n(y)|^2 \right)^{1/2}, \quad x, y \in K_d. \quad (9)$$

Observe that  $R_0 = S$  and that  $r_0(x, y) = s(x, y)$ . To obtain a rate of uniform convergence for the sequence  $(S_N)_{N \in \mathbb{N}}$ , the general assumption relies on a rate of convergence for the sequence  $(r_N)_{N \in \mathbb{N}}$ .

**Assumption 3.** *Let  $x_0 \in K_d$  with  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$  and let  $\rho$  be a quasi-metric on  $\mathbb{R}^d$  satisfying (7). Assume that there exist an almost sure event  $\Omega'$ , some random variables  $\gamma > 0$ ,  $\beta \in (0, 1]$ ,  $\eta \in \mathbb{R}$  and a positive random sequence  $(b(N))_{N \in \mathbb{N}}$  such that on  $\Omega'$ ,*

$$\forall N \in \mathbb{N}, \forall x, y \in B(x_0, \gamma) \cap K_d, r_N(x, y) \leq b(N) \rho(x, y)^\beta |\log(\rho(x, y))|^\eta. \quad (10)$$

Note that  $\Omega'$ ,  $\rho$  and the random variables  $\gamma, \beta, \eta$  and  $b(N)$  may depend on  $x_0$ . Note also that since Assumption 3 implies Assumption 2, according to Theorem 3.1, almost surely, there exists  $\gamma^* \in (0, \gamma)$  such that  $R_N = S - S_N$  is continuous on  $B(x_0, \gamma^*)$ . The following theorem precises the modulus of continuity of  $R_N$  with respect to  $N$  and a rate of uniform convergence.

**Theorem 3.3.** *Assume that Assumptions 1 and 3 are fulfilled.*

1. *Then, almost surely, there exists  $\gamma^* \in (0, \gamma)$  and  $C \in (0, +\infty)$  such that for*

$$|R_N(x) - R_N(y)| \leq C b(N) \sqrt{\log(N+2)} \rho(x, y)^\beta |\log \rho(x, y)|^{\eta+1/2}$$

*for all  $N \in \mathbb{N}$  and all  $x, y \in B(x_0, \gamma^*) \cap K_d$ .*

2. *Moreover, if almost surely, for all  $N \in \mathbb{N}$ ,*

$$|R_N(x_0)| \leq b(N) \sqrt{\log(N+2)}, \quad (11)$$

*then, almost surely, there exists  $\gamma^* \in (0, \gamma)$  and  $C \in (0, +\infty)$  such that*

$$|R_N(x)| \leq C b(N) \sqrt{\log(N+2)}$$

*for all  $N \in \mathbb{N}$  and all  $x \in B(x_0, \gamma^*) \cap K_d$ .*

**Proof.** See Appendix, Section B.2. □

An analogous of Corollary 3.2 holds for strengthening the previous local theorem to get uniform results on  $K_d$  or on  $B(x_0, \gamma) \cap K_d$  when  $\gamma$  is deterministic.

**Corollary 3.4.** *Assume that Assumptions 1 is fulfilled.*

1. *Assume that Assumption 3 holds for any  $x_0 \in K_d$  with the same almost sure event  $\Omega'$ , the same random variables  $\beta$  and  $\eta$ , the same sequence  $(b(N))_{N \in \mathbb{N}}$  and the same quasi-metric  $\rho$ . Then Assertion 1. of Theorem 3.3 holds replacing  $B(x_0, \gamma^*) \cap K_d$  by all the set  $K_d$ . If moreover, Equation (11) is fulfilled for some  $x_0 \in K_d$ , then*

$$\sup_{N \in \mathbb{N}} \sup_{x \in K_d} \frac{|R_N(x)|}{b(N) \sqrt{\log(N+2)}} < +\infty \quad \text{almost surely.}$$

2. *Assume now that Assumption 3 holds with a deterministic  $\gamma$ . Then Theorem 3.3 holds replacing  $B(x_0, \gamma^*) \cap K_d$  by  $B(x_0, \gamma) \cap K_d$ .*

## 4. Shot noise series

### 4.1. Preliminaries

In this section, we consider the sequence of shot noise series defined by

$$\forall N \in \mathbb{N}, \forall \alpha \in K_1 = [a, b] \subset (0, 2), S_N^*(\alpha) = \sum_{n=1}^N T_n^{-1/\alpha} X_n,$$

where for all  $n \geq 1$ , the random variable  $T_n$  is the  $n$ th arrival time of a Poisson process with intensity 1 and  $(X_n)_{n \geq 1}$  is a sequence of i.i.d. symmetric random variables, which is assumed independent of  $(T_n)_{n \geq 1}$ . Let us first recall that  $S_N^*(\alpha)$  converges almost surely to  $S^*(\alpha)$  an  $\alpha$ -stable random variable as soon as  $X_n \in L^\alpha$  (see [Samorodnitsky and Taqqu \(1994\)](#) for instance). Under a strengthened assumption on the integrability of  $X_n$ , rate of pointwise almost sure convergence and rate of absolute convergence have also been given in Theorems 2.1 and 2.2 of [Cohen et al. \(2008\)](#).

Since  $(X_n)_{n \geq 1}$  may not be a sequence of sub-Gaussian random variables, we cannot apply Section 3 to the sequence  $(S_N^*)_{N \in \mathbb{N}}$ . However, due to symmetry of  $(X_n)_{n \geq 1}$ ,

$$(X_n)_{n \geq 1} \stackrel{(d)}{=} (X_n g_n)_{n \geq 1}$$

with  $(g_n)_{n \geq 1}$  a Rademacher sequence independent of  $(X_n, T_n)_{n \geq 1}$  and Section 3 allows to study

$$S_N(\alpha) = \sum_{n=1}^N W_n(\alpha) g_n \quad \text{with } W_n(\alpha) := T_n^{-1/\alpha} X_n.$$

Moreover, in Theorems 3.1 and 3.3,  $S_N$  (respectively  $R_N = S - S_N$ ) can be replaced by  $S_N^*$  (respectively  $R_N^* = S^* - S_N^*$ ), see the proof of next theorem for details. Then, assuming that  $X_n$  is sufficiently integrable, we obtain the uniform convergence of  $S_N^*$  on a deterministic compact interval  $K_1 = [a, b] \subset (0, 2)$  and a rate of uniform convergence. These results, stated in the following theorem, strengthen Theorem 2.1 of [Cohen et al. \(2008\)](#) which deals with the pointwise rate of convergence.

**Theorem 4.1.** *For any integer  $n \geq 1$ , let  $T_n$  be the  $n$ th arrival time of a Poisson process with intensity 1. Let  $(X_n)_{n \geq 1}$  be a sequence of i.i.d. symmetric random variables, which is assumed independent of  $(T_n)_{n \geq 1}$ . Furthermore assume that  $\mathbb{E}(|X_1|^{2p}) < +\infty$  for some  $p > 0$ .*

1. *Then, almost surely, for all  $b \in (0, \min(2, 2p))$  and for all  $a \in (0, b]$ , the sequence of partial sums  $(S_N^*)_{N \in \mathbb{N}}$  converges uniformly on  $[a, b]$ .*
2. *Moreover, almost surely, for all  $b \in (0, \min(2, 2p))$  and for all  $a \in (0, b)$ , for all  $p' > 0$  with  $1/p' \in (0, 1/b - 1/\min(2p, 2))$ ,*

$$\sup_{N \in \mathbb{N}} \sup_{\alpha \in [a, b]} N^{1/p'} \left| \sum_{n=N+1}^{+\infty} T_n^{-1/\alpha} X_n \right| < +\infty.$$

**Proof.** See Appendix, Section C.1.  $\square$

## 4.2. Modulus of continuity and rate of convergence of shot noise series

In this section, we focus on some shot noise series, which are particular examples of conditionally sub-Gaussian series. For this purpose we assume that the following assumption is fulfilled.

**Assumption 4.** Let  $(T_n)_{n \geq 1}$ ,  $(V_n)_{n \geq 1}$  and  $(g_n)_{n \geq 1}$  be independent sequences satisfying the following conditions.

1.  $(g_n)_{n \geq 1}$  is a sequence of independent complex-valued symmetric sub-Gaussian random variables with parameter  $s = 1$ .
2.  $T_n$  is the  $n$ th arrival time of a Poisson process with intensity 1.
3.  $(V_n)_{n \geq 1}$  is a sequence of i.i.d. complex-valued random fields defined on  $K_{d+1} \subset (0, 2) \times \mathbb{R}^d$ .
4. For any  $(\alpha, u) \in K_{d+1}$ ,  $V_n(\alpha, u) \in L^\alpha$ .

For any integer  $n \geq 1$ , we consider the complex-valued random field  $W_n$  defined by

$$W_n(\alpha, u) := T_n^{-1/\alpha} V_n(\alpha, u), \quad (\alpha, u) \in K_{d+1} \subset (0, 2) \times \mathbb{R}^d. \quad (12)$$

Since  $|V_n(\alpha, u)|^2 \in L^{\alpha/2}$  and  $\alpha/2 \in (0, 1)$ , according to Theorem 1.4.5 of Samorodnitsky and Taqqu (1994),

$$\sum_{n=1}^{+\infty} |W_n(\alpha, u)|^2 = \sum_{n=1}^{+\infty} T_n^{-2/\alpha} |V_n(\alpha, u)|^2 < +\infty \quad \text{almost surely.}$$

Therefore the independent sequences  $(W_n)_{n \geq 1}$  and  $(g_n)_{n \geq 1}$  satisfy Assumption 1. Then,  $S$  and  $(S_N)_{N \in \mathbb{N}}$  are well-defined on  $K_{d+1} \subset (0, 2) \times \mathbb{R}^d \subset \mathbb{R}^{d+1}$  by (5) and (4). Before we study, the modulus of continuity of  $S$  and the rate of convergence of  $(S_N)_{N \in \mathbb{N}}$ , let us state some remarks.

**Remark 4.1.** Assume that Conditions 1–3 of Assumption 4 are fulfilled with  $(g_n)_{n \geq 1}$  a sequence of i.i.d. random variables. Then Remark 2.6 of Rosiński (1990) proves that Condition 4 is a necessary and sufficient condition for the almost sure convergence of  $(S_N(\alpha, u))_{N \in \mathbb{N}}$  for each  $(\alpha, u) \in K_{d+1}$ . Note that by Itô-Nisio Theorem (see e.g. Theorem 6.1 of Ledoux and Talagrand (1991)), it is also a necessary and sufficient condition for the convergence in distribution of the sequence  $(S_N(\alpha, u))_{N \in \mathbb{N}}$ . Then, Condition 4 is not a strong assumption and is clearly essential to ensure that  $S(\alpha, u)$  is well-defined.

**Remark 4.2.** Assume that Assumption 4 is fulfilled with  $(g_n)_{n \geq 1}$  a sequence of i.i.d. random variables. Then, it is well-known that for each  $\alpha \in (0, 2)$ ,  $S(\alpha, \cdot)$  is an  $\alpha$ -stable symmetric random field, as field in variable  $u$ . In Section 5.1, we will focus on  $\alpha$ -stable random fields defined through a stochastic integral and see that, up to a multiplicative constant, such a random field  $X_\alpha$  has the same finite distributions as  $S(\alpha, \cdot)$  for a suitable choice of  $(g_n, V_n)_{n \geq 1}$ . The sample path regularity of  $S$  in its variable  $\alpha$  is not needed to obtain an upper bound of the modulus of continuity of  $X_\alpha$ . Nevertheless, this regularity is useful to deal with multistable random fields (see Section 5.2).

The sequel of this section is devoted to simple criteria, based on some moments of  $V_n$ , which ensure that Assumption 3 (and then Assumption 2) is fulfilled. More precisely, the results given below help us to give simple conditions in order to get Assumption 3 and (11) satisfied with  $b(N) = (N + 1)^{-1/p'}$  for some convenient  $p' > 0$ . Then, all the results of Section 3 hold.

**Theorem 4.2.** Assume that Assumption 4 is fulfilled with  $K_{d+1} = [a, b] \times \prod_{j=1}^d [a_j, b_j] \subset (0, 2) \times \mathbb{R}^d$  and let  $\rho$  be a quasi-metric on  $\mathbb{R}^{d+1}$  satisfying Equation (7). Assume also that for some  $x_0 \in K_{d+1}$ , there exist  $r \in (0, +\infty)$ ,  $\beta \in (0, 1]$ ,  $\eta \in \mathbb{R}$  and  $p \in (b/2, +\infty)$  such that  $\mathbb{E}(|V_1(x_0)|^{2p}) < +\infty$  and

$$\mathbb{E} \left( \left[ \sup_{\substack{x, y \in K_{d+1} \\ 0 < \|x - y\| \leq r}} \frac{|V_1(x) - V_1(y)|}{\rho(x, y)^\beta |\log \rho(x, y)|^\eta} \right]^{2p} \right) < \infty. \quad (13)$$

Let us recall that  $S$  and  $S_N$  are defined by (5) and (4) with  $W_n$  given by (12).

1. Then, almost surely  $(S_N)_{N \in \mathbb{N}}$  converges uniformly on  $K_{d+1}$  and its limit  $S$  belongs almost surely to  $\mathcal{H}_\rho(K_{d+1}, \beta, \max(\eta, 0) + 1/2)$ .
2. Moreover, when  $p' > 0$  is such that  $1/p' \in (0, 1/b - 1/\min(2p, 2))$ , almost surely

$$\sup_{N \in \mathbb{N}} N^{1/p'} \sup_{x \in K_{d+1}} |S(x) - S_N(x)| < +\infty.$$

**Proof.** See Appendix, Section C.2. □

**Example 4.1.** Assume that  $V_1$  is a fractional Brownian field on  $\mathbb{R}^d$  with Hurst parameter  $H$ . Then (13) is satisfied for all  $p > 0$  with  $\rho(x, y) = \|x - y\|$ ,  $\beta = H$  and  $\eta = 1/2$  (see e.g. Theorem 1.3 of Benassi et al. (1997)).

Let us now present a method (similar to those used in Kôno and Maejima (1991a); Biermé and Lacaux (2009); Biermé et al. (2011) to bound some conditional variance) to establish (13).

**Proposition 4.3.** *Let  $x_0 = (\alpha_0, u_0) \in K_{d+1}$  with  $K_{d+1} = [a, b] \times \prod_{j=1}^d [a_j, b_j] \subset (0, 2) \times \mathbb{R}^d$ . Let  $V_1$  be a complex-valued random field defined on  $K_{d+1}$ . Assume that there exists a random field  $(\mathcal{G}(h))_{h \in [0, +\infty)}$  with values in  $[0, \infty)$  and such that*

(i). *there exists  $\rho$  a quasi-metric on  $\mathbb{R}^{d+1}$  satisfying Equation (7) such that almost surely,*

$$\forall x, y \in K_{d+1}, |V_1(x) - V_1(y)| \leq \mathcal{G}(\rho(x, y));$$

(ii). *there exists  $h_0 \in (0, 1]$  such that almost surely, the function  $h \mapsto \mathcal{G}(h)$  is monotonic on  $[0, h_0]$ ;*

(iii). *there exist  $p > b/2$  and some constants  $\beta \in (0, 1]$ ,  $\eta \in \mathbb{R}$  and  $C \in (0, \infty)$  such that for some  $\varepsilon > 0$  and for  $h > 0$  small enough,*

$$I(h) := \mathbb{E}(\mathcal{G}(h)^{2p}) \leq Ch^{2p\beta} |\log h|^{2p(\eta - 1/2p - \varepsilon)}. \quad (14)$$

Then, Equation (13) holds for  $r > 0$  small enough.

**Proof.** See Appendix, Section C.2. □

**Remark 4.3.** *If  $(V_n)_{n \geq 1}$  is a sequence of independent symmetric random variables, Theorem 4.2 still holds replacing  $S_N(\alpha, u)$  (respectively  $S(\alpha, u)$ ) by*

$$S_N^*(\alpha, u) = \sum_{n=1}^N T_n^{-1/\alpha} V_n(\alpha, u) \quad (\text{respectively by } S^*(\alpha, u) = \sum_{n=1}^{+\infty} T_n^{-1/\alpha} V_n(\alpha, u)).$$

*In particular, following Example 4.1, when Assumption 4 is fulfilled with  $V_1$  a fractional Brownian field on  $\mathbb{R}^d$  with Hurst parameter  $H$ , Assumptions of Theorem 4.2 are fulfilled with  $\rho_{d+1}$  the Euclidean distance on  $\mathbb{R}^{d+1}$ ,  $\beta = H$  and  $\eta = 1/2$ , on any compact  $(d+1)$ -dimensional interval  $K_{d+1}$ . Especially, this leads to an upper bound of the modulus of continuity of  $S^*$  on any compact  $(d+1)$ -dimensional interval  $K_{d+1}$ . Then for any fixed  $\alpha_0 \in (0, 2)$ , we also obtain that the  $\alpha_0$ -stable random field  $(S^*(\alpha_0, u))_{u \in \mathbb{R}^d}$  is in  $\mathcal{H}_{\rho_d}(K_d, H, 1)$  for  $\rho_d$  the Euclidean distance on  $\mathbb{R}^d$  and for any compact set  $K_d \subset \mathbb{R}^d$ .*

### 4.3. LePage random series representation

Representations in random series of infinitely divisible laws have been studied in LePage (1989, 1981). Such representations have been successfully used to study sample path properties of some symmetric  $\alpha_0$ -stable random processes ( $d = 1$ ) and fields (see e.g. Kôno and Maejima (1991a); Biermé and Lacaux (2009); Biermé et al. (2011); Dozzi and Shevchenko (2011)).

Let us be more precise on the assumptions on the LePage series under study.

**Assumption 5.** *Let  $(T_n)_{n \geq 1}$  and  $(g_n)_{n \geq 1}$  be as in Assumption 4. Let  $(\xi_n)_{n \geq 1}$  be a sequence of i.i.d. random variables with common law*

$$\mu(d\xi) = m(\xi)\nu(d\xi)$$

equivalent to a  $\sigma$ -finite measure  $\nu$  on  $(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d))$  (that is such that  $m(\xi) > 0$  for  $\nu$ -almost every  $\xi$ ). This sequence is independent from  $(g_n, T_n)_{n \geq 1}$ . Moreover we consider

$$V_n(\alpha, u) := f_\alpha(u, \xi_n) m(\xi_n)^{-1/\alpha},$$

where for any  $\alpha \in K_1 \subset (0, 2)$ ,  $f_\alpha : K_d \times \mathbb{R}^d \rightarrow \mathbb{C}$  is a deterministic function such that

$$\forall u \in K_d \subset \mathbb{R}^d, \int_{\mathbb{R}^d} |f_\alpha(u, \xi)|^\alpha \nu(d\xi) < +\infty.$$

Under this assumption, Assumption 4 is fulfilled with  $K_{d+1} = K_1 \times K_d$ . Then, emphasizing the dependence on the function  $m$ ,  $S_{m,N}$  and  $S_m$  are well-defined on  $K_{d+1}$  by (4) and (5) with  $W_n$  given by (12). In particular,

$$S_m(\alpha, u) = \sum_{n=1}^{+\infty} T_n^{-1/\alpha} f_\alpha(u, \xi_n) m(\xi_n)^{-1/\alpha} g_n, \quad (\alpha, u) \in K_{d+1} := K_1 \times K_d \subset (0, 2) \times \mathbb{R}^d. \quad (15)$$

Under appropriate assumptions on  $f_\alpha$  and  $m$ , the previous sections state the uniform convergence of the series, give a rate of convergence and some results on regularity for  $S_m$ . Precise results on regularity of  $S_m$  may be obtained using the following proposition, which states that the finite distributions of  $S_m$  does not depend on the choice of the  $\nu$ -density  $m$ .

**Proposition 4.4.** *Assume that Assumption 5 is fulfilled and let  $S_m$  be defined by (15). Let  $(\tilde{\xi}_n)_{n \geq 1}$  be a sequence of i.i.d. random variables with common law  $\tilde{\mu}(d\xi) = \tilde{m}(\xi) \nu(d\xi)$  equivalent to  $\nu$ . Assume that the sequences  $(\tilde{\xi}_n)_{n \geq 1}$ ,  $(g_n)_{n \geq 1}$  and  $(T_n)_{n \geq 1}$  are independent.*

1. *Then,  $S_m \stackrel{fdd}{=} S_{\tilde{m}}$ , where  $\stackrel{fdd}{=}$  means equality of finite distributions. In other words,*

$$(S_m(\alpha, u))_{(\alpha, u) \in K_{d+1}} \stackrel{fdd}{=} \left( \sum_{n=1}^{+\infty} T_n^{-1/\alpha} f_\alpha(u, \tilde{\xi}_n) \tilde{m}(\tilde{\xi}_n)^{-1/\alpha} g_n \right)_{(\alpha, u) \in K_{d+1}}.$$

2. *Assume moreover that for  $\nu$ -almost every  $\xi \in \mathbb{R}^d$ , the map  $(\alpha, u) \mapsto f_\alpha(u, \xi)$  is continuous on the compact set  $K_{d+1} \subset (0, 2) \times \mathbb{R}^d$ . Let us consider  $\rho$  a quasi-metric on  $\mathbb{R}^{d+1}$ ,  $\beta \in (0, 1]$  and  $\eta \in \mathbb{R}$ . Then,  $S_m$  belongs almost surely in  $\mathcal{H}_\rho(K_{d+1}, \beta, \eta)$  if and only if  $S_{\tilde{m}}$  does.*

**Proof.** See Appendix, Section C.3. □

In particular, when studying the sample path properties of  $S_m$ , this result allows us to replace  $m$  by an other function  $\tilde{m}$  so that the regularity of  $S_m$  may be deduced from the regularity of  $S_{\tilde{m}}$ . For example, replacing  $m$  by  $m_{x_0}$  depending on  $x_0$  this may lead to a more precised bound for the modulus of continuity of  $S_m$  around  $x_0$  (see e.g. Example 5.3).



## 5. Applications

### 5.1. $\alpha$ -stable isotropic random fields

Let us fix  $\alpha = \alpha_0 \in (0, 2)$  and assume that Assumption 5 is fulfilled with  $g_n$  some isotropic complex random variables. Then, the proof of Proposition 4.4 (see Section C.3) allows to compute the characteristic function of the isotropic  $\alpha_0$ -stable random field  $S_m(\alpha_0, \cdot) = (S_m(\alpha_0, u))_{u \in K_d}$ , which leads to

$$S_m(\alpha_0, \cdot) \stackrel{fdd}{=} d_{\alpha_0} \left( \int_{\mathbb{R}^d} f_{\alpha_0}(u, \xi) M_{\alpha_0}(d\xi) \right)_{u \in K_d},$$

with  $M_{\alpha_0}$  a complex isotropic  $\alpha_0$ -stable random measure on  $\mathbb{R}^d$  with control measure  $\nu$  and

$$d_{\alpha_0} = \mathbb{E}(|\Re(g_1)|^{\alpha_0})^{1/\alpha_0} \left( \frac{1}{2\pi} \int_0^{2\pi} |\cos(\theta)|^{\alpha_0} d\theta \right)^{-1/\alpha_0} \left( \int_0^{+\infty} \frac{\sin(\theta)}{\theta^{\alpha_0}} d\theta \right)^{1/\alpha_0}. \quad (16)$$

When  $\nu$  is a finite measure (respectively the Lebesgue measure), this stochastic integral representation of  $S_m(\alpha_0, \cdot)$  has been provided in Samorodnitsky and Taqqu (1994); Marcus and Pisier (1984) (respectively Kôno and Maejima (1991a); Biermé and Lacaux (2009)).

Let us note that assumptions of Theorem 4.2 and Proposition 4.3 can be stated in term of the deterministic kernel  $f_{\alpha_0}$  to obtain an upper bound of the modulus of continuity of  $S_m$ . In general, well-choosing  $m_{u_0}$  and applying Proposition 4.4, we obtain a more precise upper bound of the modulus of continuity of  $S_m(\alpha_0, \cdot)$  around  $u_0$ , which also holds for a modification of the random field

$$X_{\alpha_0} = \left( \int_{\mathbb{R}^d} f_{\alpha_0}(u, \xi) M_{\alpha_0}(d\xi) \right)_{u \in K_d}. \quad (17)$$

To illustrate how the previous sections can be applied to study the field  $X_{\alpha_0}$ , which is defined through a stochastic integral and not a series, let us focus on the case of harmonizable stable random fields. More precisely, we consider

$$f_{\alpha_0}(u, \xi) = (e^{i\langle u, \xi \rangle} - 1) \psi_{\alpha_0}(\xi), \quad \forall (u, \xi) \in \mathbb{R}^d \times \mathbb{R}^d, \quad (18)$$

with  $\psi_{\alpha_0} : \mathbb{R}^d \rightarrow \mathbb{C}$  a borelian function such that

$$\int_{\mathbb{R}^d} \min(1, \|\xi\|^{\alpha_0}) |\psi_{\alpha_0}(\xi)|^{\alpha_0} \nu(d\xi) < +\infty.$$

Note that, since this assumption does not depend on  $u$ , the random field  $X_{\alpha_0}$  may be defined on the whole space  $\mathbb{R}^d$ . For the sake of simplicity, in the sequel, we consider the case where  $\nu$  is the Lebesgue measure and first focus on a random field  $X_{\alpha_0}$  which behaves as operator scaling random fields studied in Biermé et al. (2007).

**Proposition 5.1.** *Let  $\alpha_0 \in (0, 2)$  and let  $X_{\alpha_0}$  be defined by (17) with  $\nu$  the Lebesgue measure on  $\mathbb{R}^d$ . Let  $E$  be a real matrix of size  $d \times d$  whose eigenvalues have positive real parts. Let  $\tau_E$  and  $\tau_{E^t}$  be functions as introduced in Example 2.1 and let us set  $q(E) = \text{trace}(E)$  and  $a_1 = \min_{\lambda \in \text{Sp}(E)} \Re(\lambda)$  with  $\text{Sp}(E)$  the spectrum of  $E$ , that is the set of the eigenvalues of  $E$ . Assume that there exist some finite positive constants  $c_\psi$ ,  $A$  and  $\beta \in (0, a_1)$  such that*

$$|\psi_{\alpha_0}(\xi)| \leq c_\psi \tau_{E^t}(\xi)^{-\beta - q(E)/\alpha_0}, \quad \text{for almost every } \|\xi\| > A. \quad (19)$$

*Then, there exists a modification  $X_{\alpha_0}^*$  of  $X_{\alpha_0}$  such that almost surely, for any  $\varepsilon > 0$ , for any non-empty compact set  $K_d \subset \mathbb{R}^d$ ,*

$$\sup_{\substack{u, v \in K_d \\ u \neq v}} \frac{|X_{\alpha_0}^*(u) - X_{\alpha_0}^*(v)|}{\tau_E(u - v)^\beta \left[ \log \left( 1 + \tau_E(u - v)^{-1} \right) \right]^{\varepsilon + 1/2 + 1/\alpha_0}} < +\infty.$$

**Remark 5.1.** *The quasi-metric  $(x, y) \mapsto \tau_E(x - y)$  may not fulfill Equation (7) since the eigenvalues of  $E$  may not be greater than 1. Nevertheless, the quasi-metric  $(x, y) \mapsto \tau_{E/a_1}(x - y)$  does and the conclusion with  $\tau_E$  in the previous proposition then follows from the comparison*

$$\forall \xi \in \mathbb{R}^d, \quad c_1 \tau_E(\xi)^{a_1} \leq \tau_{E/a_1}(\xi) \leq c_2 \tau_E(\xi)^{a_1}$$

*with  $c_1, c_2$  two finite positive constants.*

**Proof.** See Appendix, Section D.1. □

An upper bound for the modulus of continuity of such harmonizable random fields is also obtained in Xiao (2010). This upper bound is given in term of the Euclidean norm and then does not take into account the anisotropic behavior of  $X_{\alpha_0}$ . Even when  $\tau_E$  is the Euclidean norm, our result is a little more precise than the one of Xiao (2010). The difference is only in the power of the logarithmic term.

Let us now give some examples. We keep the notation of the previous proposition and the eigenvalues of the matrix  $E$  have always positive real parts.

**Example 5.1. (Operator scaling random fields Biermé et al. (2007))** *Let  $\psi : \mathbb{R}^d \rightarrow [0, \infty)$  be an  $E^t$ -homogeneous function, which means that*

$$\forall c \in (0, +\infty), \forall \xi \in \mathbb{R}^d, \quad \psi(c^{E^t} \xi) = c\psi(\xi)$$

*where  $c^{E^t} = \exp(E^t \log c)$ . Let us assume that  $\psi$  is a continuous function such that  $\psi(\xi) \neq 0$  for  $\xi \neq 0$ . Then we consider the function  $\psi_{\alpha_0} : \mathbb{R}^d \rightarrow [0, +\infty]$  defined by*

$$\psi_{\alpha_0}(\xi) = \psi(\xi)^{-H - q(E)/\alpha_0}.$$

The random field  $X_{\alpha_0}$ , associated with  $\psi_{\alpha_0}$  by (17) and (18), is well-defined and is stochastically continuous if and only if  $H \in (0, a_1)$ . Then, let us now fix  $H \in (0, a_1)$ . Since  $\psi_{\alpha_0}$  is  $E^t$ -homogeneous, one easily checks that there exists  $c_\psi \in (0, +\infty)$  such that

$$\forall \xi \in \mathbb{R}^d, \psi_{\alpha_0}(\xi) \leq c_\psi \tau_{E^t}(\xi)^{-H-q(E)/\alpha_0}.$$

Then, the assumptions of Proposition 5.1 are fulfilled with  $\beta = H$ . The corresponding conclusion was stated in Theorem 5.1 of Biermé and Lacaux (2009) when  $H = 1$  and  $a_1 > 1$ , which is enough to cover the general case using Remark 2.1 of Biermé and Lacaux (2009).

**Example 5.2. (Anisotropic Riesz-Bessel  $\alpha$ -stable random fields)** Let us consider

$$\psi_{\alpha_0}(\xi) = \frac{1}{\tau_{E^t}(\xi)^{2\beta_1/\alpha_0} (1 + \tau_{E^t}(\xi)^2)^{\beta_2/\alpha_0}}, \quad \xi \in \mathbb{R}^d \setminus \{0\}$$

with two real numbers  $\beta_1$  and  $\beta_2$ . Assuming that

$$\frac{q(E)}{2} < \beta_1 + \beta_2 \quad \text{and} \quad \beta_1 < \frac{q(E)}{2} + \frac{\alpha_0 a_1}{2},$$

the random field  $X_{\alpha_0}$  is well-defined by (17). When  $\tau_{E^t}$  is the Euclidean norm, this random field has been introduced in Xiao (2010) to generalize the Gaussian fractional Riesz-Bessel motion Anh et al. (1999).

We distinguish two cases. If  $\beta_1 + \beta_2 < \frac{q(E)}{2} + \frac{\alpha_0 a_1}{2}$ , Proposition 5.1 can be applied with  $\beta = \frac{2(\beta_1 + \beta_2) - q(E)}{\alpha_0}$ . Otherwise, Proposition 5.1 can be applied for any  $\beta \in (0, a_1)$ .

Random fields defined by (17) have stationary increments so that their regularity on  $K_d$  does not depend on the compact set  $K_d$ . To avoid this feature one can consider non-stationary generalizations by substituting  $\psi_{\alpha_0}$  by a function that also depends on  $u \in K_d$ . More precisely, we can consider

$$X_{\alpha_0} = \left( \int_{\mathbb{R}^d} \left( e^{i\langle u, \xi \rangle} - 1 \right) \psi_{\alpha_0}(u, \xi) M_{\alpha_0}(d\xi) \right)_{u \in K_d} \quad (20)$$

with  $M_{\alpha_0}$  a complex isotropic  $\alpha_0$ -stable random measure with Lebesgue control measure and  $\psi_{\alpha_0}$  a borelian function such that, for all  $u \in K_d$ ,

$$\int_{\mathbb{R}^d} \left| e^{i\langle u, \xi \rangle} - 1 \right|^{\alpha_0} |\psi_{\alpha_0}(u, \xi)|^{\alpha_0} d\xi < +\infty.$$

Under some conditions on  $\psi_{\alpha_0}$ , when considering the local behavior of  $X_{\alpha_0}$  around a point  $u_0$  one can conveniently choose a Lebesgue density  $m_{u_0}$  to obtain an upper bound of the modulus of continuity of the shot noise series  $S_{m_{u_0}}(\alpha_0, \cdot)$  given by (15) with

$$f_{\alpha_0}(u, \xi) = \left( e^{i\langle u, \xi \rangle} - 1 \right) \psi_{\alpha_0}(u, \xi).$$

For the sake of conciseness, let us illustrate this with multi-operator random fields, which have already been studied in [Biermé et al. \(2011\)](#).

**Example 5.3. (Multi-operator scaling  $\alpha$ -stable random fields)** In [Biermé et al. \(2011\)](#), we consider  $E$  a function defined on  $\mathbb{R}^d$  with values in the set of real matrix of size  $d \times d$  whose eigenvalues have real parts greater than 1 and  $\psi : \mathbb{R}^d \times \mathbb{R}^d \rightarrow [0, +\infty)$  a continuous function such that for any  $u \in \mathbb{R}^d$ ,  $\psi(u, \cdot)$  is homogeneous with respect to  $E(u)^t$  i.e.

$$\psi(u, c^{E(u)^t} \xi) = c\psi(u, \xi), \forall \xi \in \mathbb{R}^d, \forall c > 0.$$

Under convenient regularity assumptions on  $\psi$  and  $E$ , the  $\alpha_0$ -stable random field  $X_{\alpha_0}$  is well-defined by (20) setting

$$\psi_{\alpha_0}(u, \xi) = \psi(u, \xi)^{-1-q(E(u))/\alpha_0} \text{ with } q(E(u)) = \text{trace}(E(u)).$$

Let  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$  and  $u_0 \in K_d$ . Let us set  $K_{d+1} = \{\alpha_0\} \times K_d$  and consider the quasi-metric  $\rho$  defined on  $\mathbb{R}^{d+1}$  by

$$\rho((\alpha, u), (\alpha', v)) = |\alpha - \alpha'| + \tau_{E(u_0)}(u - v)$$

for all  $(\alpha, u), (\alpha', v) \in \mathbb{R} \times \mathbb{R}^d$ , which clearly satisfies Equation (7). Then, under assumptions of [Biermé et al. \(2011\)](#), there exists a Lebesgue density  $m_{u_0} > 0$  a.e. such that Assumption 2 holds for  $S_{m_{u_0}}$  on  $K_{d+1}$  with  $\eta = 0$  and all  $\beta \in (0, 1)$ , adapting similar arguments as in Proposition 5.1 (see Lemma 4.7 of [Biermé et al. \(2011\)](#)). Therefore, following a part of the proof of Proposition 5.1, there exists a modification  $X_{\alpha_0}^*$  of  $X_{\alpha_0}$  such that almost surely,

$$\lim_{r \downarrow 0} \sup_{\substack{u, v \in B(u_0, r) \cap K_d \\ u \neq v}} \frac{|X_{\alpha_0}^*(u) - X_{\alpha_0}^*(v)|}{\tau_{E(u_0)}(u - v)^{1-\varepsilon}} < +\infty$$

for any  $\varepsilon \in (0, 1)$ . This is Theorem 4.6 of [Biermé et al. \(2011\)](#).

For the sake of conciseness, we do not develop other examples. Nevertheless, let us mention that our results can also be applied to harmonizable fractional  $\alpha$ -stable sheets or even to operator stable sheets. In particular, this improves the result stated in [Mason and Xiao \(2001\)](#) for fractional  $\alpha$ -stable sheets. Note that we can also deal with real symmetric measure  $W_\alpha$ .

## 5.2. Multistable random fields

Multistable random fields have first been introduced in [Falconer and Lévy Véhel \(2009\)](#) and then studied in [Falconer et al. \(2009\)](#). Each marginal  $X(u)$  of such a random field is a stable random variable but its stability index is allowed to depend on the position  $u$ .

Generalizing the class of multistable random fields introduced in [Le Guével and Lévy Véhel \(2012\)](#), we consider a multistable random field defined by a LePage series. More precisely, under Assumption 5, we consider

$$\tilde{S}_m(u) = \sum_{n=1}^{+\infty} T_n^{-1/\alpha(u)} f_{\alpha(u)}(u, \xi_n) m(\xi_n)^{-1/\alpha(u)} g_n, \quad u \in K_d \quad (21)$$

where  $\alpha : K_d \rightarrow (0, 2)$  is a function. Then since  $\tilde{S}_m(u) = S_m(\alpha(u), u)$  with  $S_m$  defined by (15), we deduce from Section 4 an upper bound for the modulus of continuity of  $\tilde{S}$ . In particular, assuming that  $\alpha$  is smooth enough, we obtain the following theorem.

**Proposition 5.2.** *Let  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$ . Let us choose  $u_0 \in K_d$ . Let  $\tilde{\rho}$  be a quasi-metric on  $\mathbb{R}^d$  satisfying Equation (7) and let  $\alpha : K_d \rightarrow (0, 2)$  belongs to  $\mathcal{H}_{\tilde{\rho}}(K_d, 1, 0)$ . Let us set*

$$a = \min_{K_d} \alpha, \quad b = \max_{K_d} \alpha \quad \text{and} \quad K_1 = [a, b] \subset (0, 2)$$

and consider the quasi-metric  $\rho$  defined on  $\mathbb{R} \times \mathbb{R}^d$  by

$$\rho((\alpha, u), (\alpha', v)) = |\alpha - \alpha'| + \tilde{\rho}(u, v).$$

Assume that Assumption 5 is fulfilled and that Equation (13) holds on  $K_{d+1} = [a, b] \times K_d$  for some  $p > b/2$ ,  $\beta \in (0, 1]$  and  $\eta \in \mathbb{R}$ . Assume also that

$$\mathbb{E}(|V_1(\alpha(u_0), u_0)|^{2p}) = \int_{\mathbb{R}^d} |f_{\alpha(u_0)}(u_0, \xi)|^{2p} m(\xi)^{1-2p/\alpha(u_0)} d\xi < +\infty.$$

Let  $S_{m,N}$  be defined by (4) with  $W_n(\alpha, u) = T_n^{-1/\alpha} f_{\alpha}(u, \xi_n) m(\xi_n)^{-1/\alpha}$  and let  $\tilde{S}_{m,N}(u) = S_{m,N}(\alpha(u), u)$ .

1. Then, almost surely,  $(\tilde{S}_{m,N})_{N \in \mathbb{N}}$  converges uniformly on  $K_d$  to  $\tilde{S}_m$  and almost surely the limit  $\tilde{S}_m$  belongs to  $\mathcal{H}_{\tilde{\rho}}(K_d, \beta, \max(\eta, 0) + 1/2)$ .
2. Moreover, for all  $p' > 0$  such that  $1/p' \in (0, 1/b - 1/\min(2p, 2))$ ,

$$\sup_{N \in \mathbb{N}} N^{1/p'} \sup_{u \in K_d} |\tilde{S}_m(u) - \tilde{S}_{m,N}(u)| < +\infty.$$

**Proof.** See Appendix, Section D.2. □

**Remark 5.2.** Let us recall that  $\tilde{S}_m \in \mathcal{H}_{\tilde{\rho}}(K_d, \beta, \max(\eta, 0) + 1/2)$  if and only if  $\tilde{S}_{\tilde{m}} \in \mathcal{H}_{\tilde{\rho}}(K_d, \beta, \max(\eta, 0) + 1/2)$ , with  $\tilde{m}$  an other  $\nu$ -density equivalent to  $\nu$ , by Proposition 4.4.

To illustrate the previous proposition, we only focus on multistable random fields obtained replacing in a LePage series representation of an harmonizable operator scaling stable random field the index  $\alpha$  by a function. Many other examples can be given, such as multistable anisotropic Riesz-Bessel random fields or the class of linear multistable random fields defined in [Falconer et al. \(2009\)](#).

**Corollary 5.3 (Multistable versions of harmonizable operator scaling random fields).** *Let  $E$  be a real matrix of size  $d \times d$  such that  $\min_{\lambda \in \text{Sp} E} \Re(\lambda) > 1$ . Let us consider  $\rho_E$  and  $\tau_E$  as defined in Example 2.1. Let us also consider  $\psi : \mathbb{R}^d \rightarrow [0, \infty)$  a continuous,  $E^t$ -homogeneous function such that  $\psi(\xi) \neq 0$  for  $\xi \neq 0$ . Then we set*

$$f_\alpha(u, \xi) = \left( e^{i\langle u, \xi \rangle} - 1 \right) \psi(\xi)^{-1-q(E)/\alpha}$$

with  $q(E) = \text{trace}(E)$ . Let  $m$  be a Lebesgue density a.e. positive on  $\mathbb{R}^d$ ,  $(\xi_n, T_n, g_n)_{n \geq 1}$  be as in Assumption 5 with  $\nu$  the Lebesgue measure and consider a function  $\alpha : \mathbb{R}^d \rightarrow (0, 2)$ . Therefore, the multistable random field  $\tilde{S}_m$  is well-defined by (21) on the whole space  $\mathbb{R}^d$ . Moreover if  $\alpha \in \mathcal{H}_{\rho_E}(\mathbb{R}^d, 1, 0)$ , then for any  $u_0 \in \mathbb{R}^d$  and  $\varepsilon > 0$ , there exists  $r \in (0, 1]$  such that almost surely

$$\sup_{\substack{u, v \in B(u_0, r) \\ u \neq v}} \frac{|\tilde{S}_m(u) - \tilde{S}_m(v)|}{\tau_E(u - v) |\log \tau_E(u - v)|^{1/\alpha(u_0) + 1/2 + \varepsilon}} < +\infty.$$

**Proof.** See Appendix, Section D.2. □

**Remark 5.3.** In particular, when  $E = \text{Id}$ ,  $\tau_E$  is the Euclidean norm and we obtain an upper bound of the modulus of continuity of multistable versions of fractional harmonizable stable fields.

## Appendix A: Proof of Proposition 2.1

The proof of Proposition 2.1 is based on the following lemma.

**Lemma A.1.** *If  $Z$  is a complex-valued sub-Gaussian random variable with parameter  $s \in (0, +\infty)$ , then for all  $t \in (0, +\infty)$ ,  $\mathbb{P}(|Z| > t) \leq 4e^{-\frac{t^2}{8s^2}}$ .*

**Proof.** Let  $t \in (0, +\infty)$ . Since  $Z$  is sub-Gaussian with parameter  $s$ ,  $\Re(Z)$  and  $\Im(Z)$  are real-valued sub-Gaussian random variables with parameter  $s$ . Then applying Proposition 4 of Kahane (1960),

$$\mathbb{P}(|Z| > t) \leq \mathbb{P}\left(|\Re(Z)| > \frac{t}{2}\right) + \mathbb{P}\left(|\Im(Z)| > \frac{t}{2}\right) \leq 4 \exp\left(-\frac{t^2}{8s^2}\right),$$

which concludes the proof □

Let us now prove Proposition 2.1.

**Proof of Proposition 2.1.** Let  $t \in (0, +\infty)$ . Since Proposition 2.1 is straightforward if  $a = 0$ , we assume that  $a \neq 0$ . Since the sequence  $(g_n)_{n \geq 1}$  is symmetric, by the Lévy inequalities (see Proposition 2.3 in [Ledoux and Talagrand \(1991\)](#)), for any  $M \in \mathbb{N} \setminus \{0\}$ ,

$$\mathbb{P}\left(\sup_{1 \leq P \leq M} \left| \sum_{n=1}^P a_n g_n \right| > t \|a\|_{\ell^2}\right) \leq 2\mathbb{P}\left(\left| \sum_{n=1}^M a_n g_n \right| > t \|a\|_{\ell^2}\right).$$

We now prove that  $\sum_{n=1}^M a_n g_n$  is sub-Gaussian. By independence of the random variables  $g_n$  and since each  $g_n$  is sub-Gaussian with parameter  $s = 1$ ,

$$\forall z \in \mathbb{C}, \mathbb{E}\left(e^{\Re(\bar{z} \sum_{n=1}^M a_n g_n)}\right) = \prod_{n=1}^M \mathbb{E}\left(e^{\Re(\bar{z} a_n g_n)}\right) \leq \prod_{n=1}^M e^{\frac{|z|^2 |a_n|^2}{2}} = e^{\frac{|z|^2 s_M^2}{2}} \quad (22)$$

with  $s_M = \left(\sum_{n=1}^M |a_n|^2\right)^{1/2} \leq \|a\|_{\ell^2}$ . Hence, for any  $M \in \mathbb{N} \setminus \{0\}$ ,  $\sum_{n=1}^M a_n g_n$  is sub-Gaussian with parameter  $s_M$ . Since  $a \neq 0$ , for  $M$  large enough,  $s_M \neq 0$  and then applying Lemma A.1,

$$\forall t > 0, \mathbb{P}\left(\sup_{1 \leq P \leq M} \left| \sum_{n=1}^P a_n g_n \right| > t \|a\|_{\ell^2}\right) \leq 8 \exp\left(-\frac{t^2 \|a\|_{\ell^2}^2}{8 s_M^2}\right) \leq 8 e^{-\frac{t^2}{8}}.$$

Assertion 1. follows letting  $M \rightarrow +\infty$ .

Let us now prove Assertion 2. If there exists  $N \in \mathbb{N} \setminus \{0\}$ , such that

$$\forall n \geq N, a_n = 0,$$

then, Assertion 2. is fulfilled since  $\sum_{n=1}^{+\infty} a_n g_n = \sum_{n=1}^N a_n g_n$  is a sub-Gaussian random variable with parameter  $s_N = \left(\sum_{n=1}^N |a_n|^2\right)^{1/2} = \|a\|_{\ell^2}$ . Therefore to prove Assertion 2., we now assume that

$$\forall N \in \mathbb{N} \setminus \{0\}, \exists n \geq N, a_n \neq 0,$$

so that  $\sum_{n=N}^{+\infty} |a_n|^2 \neq 0$  for any integer  $N \geq 1$ . Then, applying Assertion 1. replacing  $a_n$  by  $a_n \mathbf{1}_{n \geq N}$ , we have

$$\forall \varepsilon > 0, \forall N \in \mathbb{N} \setminus \{0\}, \mathbb{P}\left(\sup_{P \geq N} \left| \sum_{n=N}^P a_n g_n \right| > \varepsilon\right) \leq 8 e^{-\frac{\varepsilon^2}{8 \sum_{n=N}^{+\infty} |a_n|^2}}.$$

Since  $\|a\|_{\ell^2}^2 = \sum_{n=1}^{+\infty} |a_n|^2 < +\infty$ , this implies that  $\left(\sum_{n=1}^N a_n g_n\right)_N$  is a Cauchy sequence in probability. Then, by Lemma 3.6 in [Kallenberg \(2002\)](#), the series  $\sum_{n=1}^{+\infty} a_n g_n$  converges in probability. By Itô-Nisio Theorem (see [Ledoux and Talagrand \(1991\)](#) for instance), this series also converges almost surely, since the random variables  $g_n$ ,  $n \geq 1$ , are independent. Moreover, since  $\sup_{M \geq 1} s_M^2 = \|a\|_{\ell^2}^2 < +\infty$ , Equation (22) implies the

uniform integrability of the sequence  $\left(e^{\Re(z \sum_{n=1}^M a_n g_n)}\right)_{M \geq 1}$  for any  $z \in \mathbb{C}$ . Then, letting  $M \rightarrow +\infty$  in (22), we obtain that  $\sum_{n=1}^{+\infty} a_n g_n$  is sub-Gaussian with parameter  $\|a\|_{\ell^2}$ . Moreover, we conclude the proof noting that

$$\forall t > 0, \mathbb{P}\left(\left|\sum_{n=1}^{+\infty} a_n g_n\right| > t\|a\|_{\ell^2}\right) \leq \mathbb{P}\left(\sup_{P \geq 1} \left|\sum_{n=1}^P a_n g_n\right| > t\|a\|_{\ell^2}\right) \leq 8e^{-\frac{t^2}{8}}.$$

□

## Appendix B: Main results on conditionally sub-Gaussian series

### B.1. Local modulus of continuity

This section is devoted to the proofs of the results stated in Section 3.1.

**Proof of Theorem 3.1.** Let us recall that  $x_0 \in K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$ . We assume, without loss of generality, that

$$\forall 1 \leq j \leq d, a_j < b_j.$$

Actually, if some  $a_j = b_j$ , we may identify  $(S_N)_{N \in \mathbb{N}}$  and its limits  $S$  as random fields defined on  $K_{d'} \subset \mathbb{R}^{d'}$  for  $d' < d$ . Note that if  $a_j = b_j$  for all  $1 \leq j \leq d$ , there is nothing to prove.

We also assume that  $\gamma(\omega) \in (0, 1)$ , which is not restrictive and allows us to apply Equation (7) as soon as  $\|x - y\| \leq \gamma(\omega)$  (with  $c_{2,1}$  and  $c_{2,2}$  which do not depend on  $\gamma$ ).

**First Step** We first introduce a convenient sequence  $(\mathcal{D}_{\nu_k})_{k \geq 1}$  of countable sets included on dyadics, which is linked to the quasi-metric  $\rho$ . It allows to follow some arguments of the proof of the Kolmogorov's Lemma to obtain an upper bound for the modulus of continuity of  $S$ .

Let us first introduce some notation. For any  $k \in \mathbb{N} \setminus \{0\}$  and  $j \in \mathbb{Z}^d$ , we set

$$x_{k,j} = \frac{j}{2^k}, \quad \mathcal{D}_k = \{x_{k,j} : j \in \mathbb{Z}^d\} \quad \text{and} \quad \nu_k = \min \left\{ n \in \mathbb{N} \setminus \{0\} : c_{2,2} d^{H/2} 2^{-nH} \leq 2^{-k} \right\}$$

with  $c_{2,2}$  the constant given by Equation (7). Then, choosing  $c_{2,2}$  large enough (which is not restrictive), one checks that  $(\nu_k)_{k \geq 1}$  is an increasing sequence. In particular, the sequence  $(\mathcal{D}_{\nu_k})_{k \geq 1}$  is increasing and  $\mathcal{D} = \bigcup_{k=1}^{+\infty} \mathcal{D}_k = \bigcup_{k=1}^{+\infty} \mathcal{D}_{\nu_k}$ . Moreover,  $\mathcal{D} \cap K_d$  is dense in  $K_d$  since  $a_j < b_j$  for any  $1 \leq j \leq d$ . Then, as done in Step 1 of the proof of Theorem 5.1 of [Biermé and Lacaux \(2009\)](#), one also checks that for  $k$  large enough,  $\mathcal{D}_{\nu_k} \cap K_d$  is a  $2^{-k}$  net of  $K_d$  for  $\rho$ , which means that for any  $x \in K_d$ , there exists  $j \in \mathbb{Z}^d$  such that  $\rho(x, x_{\nu_k,j}) \leq 2^{-k}$ , with  $x_{\nu_k,j} = j/2^{\nu_k} \in K_d$ .



**Second Step** This step is inspired from Step 2 of [Biermé and Lacaux \(2009\)](#); [Biermé et al. \(2011\)](#). The main difference is that we use Proposition 2.1 to obtain a uniform control in  $N$ .

For  $k \in \mathbb{N} \setminus \{0\}$  and  $(i, j) \in \mathbb{Z}^d$ , we consider

$$E_{i,j}^k = \left\{ \omega : \sup_{N \in \mathbb{N}} |S_N(x_{\nu_k,i}) - S_N(x_{\nu_k,j})| > s(x_{\nu_k,i}, x_{\nu_k,j}) \varphi(\rho(x_{\nu_k,i}, x_{\nu_k,j})) \right\}$$

with, following [Kôno \(1970\)](#),

$$\varphi(t) = \sqrt{8Ad \log \frac{1}{t}}, \quad t > 0, \quad (23)$$

for  $A > 0$  conveniently chosen later. We choose  $\delta \in (0, 1)$  and set for  $k \in \mathbb{N} \setminus \{0\}$ ,

$$\delta_k = 2^{-(1-\delta)k}, \quad I_k = \left\{ (i, j) \in (\mathbb{Z}^d \cap 2^{\nu_k} K_d)^2 : \rho(x_{\nu_k,i}, x_{\nu_k,j}) \leq \delta_k \right\} \quad \text{and} \quad E_k = \bigcup_{(i,j) \in I_k} E_{i,j}^k. \quad (24)$$

Since  $\varphi$  is a decreasing function and  $s \geq 0$ , for any  $k \in \mathbb{N} \setminus \{0\}$  and for any  $(i, j) \in I_k$

$$\mathbb{P}(E_{i,j}^k) \leq \mathbb{P}\left(\sup_{N \in \mathbb{N}} |S_N(x_{\nu_k,i}) - S_N(x_{\nu_k,j})| > s(x_{\nu_k,i}, x_{\nu_k,j}) \varphi(\delta_k)\right).$$

Since  $(g_n)_{n \geq 1}$  is a sequence of symmetric independent sub-Gaussian random variables with parameter  $s = 1$ , conditioning to  $(W_n)_{n \geq 1}$  and applying Assertion 1. of Proposition 2.1, one has

$$\forall k \in \mathbb{N} \setminus \{0\}, \forall (i, j) \in I_k, \mathbb{P}(E_{i,j}^k) \leq 8e^{-\frac{\varphi(\delta_k)^2}{8}} = 8e^{-Ad(1-\delta)k \log 2}$$

by definition of  $s$ ,  $S_N$ ,  $\varphi$  and  $\delta_k$ . Moreover, since  $K_d \subset \mathbb{R}^d$  is a compact set, using Equations (8) and the definition of  $\nu_k$ , one easily proves that there exists a finite positive constant  $c_1 \in (0, +\infty)$  such that for any  $k \in \mathbb{N} \setminus \{0\}$ ,  $\text{card } I_k \leq c_1 2^{\frac{2kd}{H}} \delta_k^{\frac{d}{H}}$ . Hence,

$$\sum_{k=1}^{+\infty} \mathbb{P}(E_k) \leq \sum_{k=1}^{+\infty} \sum_{(i,j) \in I_k} \mathbb{P}(E_{i,j}^k) \leq c_1 \sum_{k=1}^{+\infty} e^{-(A(1-\delta) - \frac{2}{H} + \frac{1-\delta}{H})kd \log 2} < +\infty$$

choosing  $A > \frac{2}{H} - \frac{1}{H}$  and  $\delta$  small enough. Then, setting

$$\Omega'' = \Omega' \cap \left( \bigcup_{k=1}^{+\infty} \bigcap_{\ell=k}^{+\infty} E_\ell^c \right)$$

with  $\Omega'$  the almost sure event introduced by Assumption 2, the Borel-Cantelli Lemma leads to  $\mathbb{P}(\Omega'') = 1$ . Moreover, by Assumption 2, for any  $\omega \in \Omega''$  there exists  $k^*(\omega)$

such that for every  $k \geq k^*(\omega)$  and for all  $x, y \in \mathcal{D}_{\nu_k}$  with  $x, y \in B(x_0, \gamma(\omega)) \cap K_d$  and  $\rho(x, y) \leq \delta_k = 2^{-(1-\delta)k}$ ,

$$\sup_{N \in \mathbb{N}} |S_N(x) - S_N(y)| \leq C \rho(x, y)^\beta |\log(\rho(x, y))|^{\eta+1/2}. \quad (25)$$

**Third Step:** In this step we prove that (25) holds, up to a multiplicative constant, for any  $x, y \in \mathcal{D}$  closed enough to  $x_0$ . This step is adapted from Step 4 of the proof of Theorem 5.1 in [Biermé and Lacaux \(2009\)](#), taking care that (25) only holds for some  $x, y \in \mathcal{D}_{\nu_k} \cap K_d$  randomly closed enough of  $x_0$ . Let us mention that this step has been omitted in the proof of the main result of [Biermé et al. \(2011\)](#) but is not trivial. We then decide to provide a proof here for the sake of completeness and clearness.

Let us now fix  $\omega \in \Omega''$  and denote by  $\kappa \geq 1$  the constant appearing in the quasi-triangle inequality satisfied by  $\rho$ . We also consider the function  $F$  defined on  $(0, +\infty)$  by

$$F(h) := h^\beta |\log(h)|^{\eta+1/2}.$$

Observe that  $F$  is a random function since  $\beta$  and  $\eta$  are random variables. Then, we choose  $k_0 = k_0(\omega) \in \mathbb{N}$  such that the three following assertions are fulfilled:

- (a)  $F$  is increasing on  $(0, \delta_{k_0}]$ , where  $\delta_k$  is given by (24),
- (b) for all  $k \geq k_0(\omega)$ ,  $\mathcal{D}_{\nu_k} \cap K_d$  is a  $2^{-k}$  net of  $K_d$  for  $\rho$
- (c)  $2^{k_0} \delta_{k_0+1} > 3\kappa^2$ .

Even if it means to choose  $k^*(\omega)$  larger, we can assume that  $k^*(\omega) \geq k_0$  and that

$$\gamma(\omega) \geq \left( \frac{\delta_{k^*(\omega)}}{3\kappa^2 c_{2,2}} \right)^{1/\underline{H}} := 2\gamma^*(\omega) \quad (26)$$

where  $\underline{H}$  and  $c_{2,2}$  are defined in Equation (7).

Let us now consider  $x, y \in \mathcal{D} \cap K_d \cap B(x_0, \gamma^*(\omega))$  such that  $x \neq y$ . Let us first note that  $x, y \in B(x_0, \gamma(\omega))$ . Moreover, since  $\|x - y\| \leq 2\gamma^*(\omega) \leq \gamma(\omega) \leq 1$ , the upper bound of Equation (7) leads to

$$3\kappa^2 \rho(x, y) \leq 3\kappa^2 c_{2,2} \|x - y\|^{\underline{H}} \leq \delta_{k^*(\omega)}$$

by definition of  $\gamma^*(\omega)$ . Then, there exists a unique  $k \geq k^*(\omega)$  such that

$$\delta_{k+1} < 3\kappa^2 \rho(x, y) \leq \delta_k. \quad (27)$$

Furthermore, since  $x, y \in \mathcal{D} \cap K_d$ , there exists  $n \geq k+1$  such that  $x, y \in \mathcal{D}_{\nu_n} \cap K_d$  and for  $j = k, \dots, n-1$ , there exist  $x^{(j)} \in \mathcal{D}_{\nu_j} \cap K_d$  and  $y^{(j)} \in \mathcal{D}_{\nu_j} \cap K_d$  such that

$$\rho(x, x^{(j)}) \leq 2^{-j} \text{ and } \rho(y, y^{(j)}) \leq 2^{-j}. \quad (28)$$

Let us now fix  $N \in \mathbb{N}$  and focus on  $S_N(x) - S_N(y)$ . Then, setting  $x^{(n)} = x$  and  $y^{(n)} = y$ ,

$$\begin{aligned} S_N(x) - S_N(y) &= \left( S_N(x^{(k)}) - S_N(y^{(k)}) \right) + \sum_{j=k}^{n-1} \left( S_N(x^{(j+1)}) - S_N(x^{(j)}) \right) \\ &\quad - \sum_{j=k}^{n-1} \left( S_N(y^{(j+1)}) - S_N(y^{(j)}) \right). \end{aligned} \quad (29)$$

The following lemma, whose proof is given below for the sake of clearness, allows to apply (25) for each term of the right hand side of the last inequality.

**Lemma B.1.** *Choosing  $k^*(\omega)$  large enough, the sequences  $(x^{(j)})_{k \leq j \leq n}$  and  $(y^{(j)})_{k \leq j \leq n}$  satisfy the three following assertions.*

1.  $x^{(j)}, y^{(j)} \in B(x_0, \gamma(\omega))$  for any  $j = k, \dots, n$ ,
2. for any  $j = k, \dots, n-1$ ,  $\max(\rho(x^{(j+1)}, x^{(j)}), \rho(y^{(j+1)}, y^{(j)})) \leq \delta_{j+1}$ ,
3.  $\rho(x^{(k)}, y^{(k)}) \leq \delta_k$ .

Therefore, even if it means to choose  $k^*(\omega)$  larger, applying this lemma and Equations (25) and (29), we obtain

$$|S_N(x) - S_N(y)| \leq C \left( F(\rho(x^{(k)}, y^{(k)})) + 2 \sum_{j=k}^{n-1} F(\delta_{j+1}) \right)$$

since  $F$  is increasing on  $(0, \delta_{k_0}]$  and since  $j \geq k_0$ . This implies, by definition of  $F$  that

$$|S_N(x) - S_N(y)| \leq C \left( F(\rho(x^{(k)}, y^{(k)})) + 2\tilde{C}F(\delta_{k+1}) \right),$$

where

$$\tilde{C}(\omega) = 2 \sum_{j=0}^{+\infty} \delta_j^{\beta(\omega)} (j+1)^{\max(\eta(\omega)+1/2, 0)} < +\infty$$

since  $\beta > 0$  and  $\delta_j = 2^{-(1-\delta)j}$  with  $\delta < 1$ . Then, since  $F$  is increasing on  $(0, \delta_0)$ , by Assertion 3. of Lemma B.1 and Equation (27), we get

$$|S_N(x) - S_N(y)| \leq C(1 + 2\tilde{C})F(3\kappa^2\rho(x, y)),$$

for every  $N \in \mathbb{N}$  and  $x, y \in \mathcal{D} \cap B(x_0, \gamma^*(\omega)) \cap K_d$ . Therefore, by continuity of  $\rho$  and each  $S_N$  and by density of  $\mathcal{D} \cap K_d$  in  $K_d$

$$|S_N(x) - S_N(y)| \leq C(1 + 2\tilde{C})F(3\kappa^2\rho(x, y)), \quad (30)$$

for every  $N \in \mathbb{N}$  and  $x, y \in B(x_0, \gamma^*(\omega)) \cap K_d$ .

**Fourth Step: Uniform convergence of  $S_N$ .** Let us now consider

$$\tilde{\Omega} = \bigcap_{u \in \mathcal{D}} \left\{ \lim_{N \rightarrow +\infty} S_N(u) = S(u) \right\} \cap \Omega''.$$

Observe that  $\mathbb{P}(\tilde{\Omega}) = 1$ . Let us now fix  $\omega \in \tilde{\Omega}$ . Hence, by Equation (30), the sequence  $(S_N(\cdot)(\omega))_{N \in \mathbb{N}}$ , which converges pointwise on  $\mathcal{D} \cap B(x_0, \gamma^*(\omega)) \cap K_d$  is uniformly equicontinuous on  $B(x_0, \gamma^*(\omega))$ . Since  $\mathcal{D} \cap B(x_0, \gamma^*(\omega)) \cap K_d$  is dense in  $B(x_0, \gamma^*(\omega)) \cap K_d$ , by Theorem I.26 and adapting Theorem I.27 in [Reed and Simon \(1972\)](#),  $(S_N(\cdot)(\omega))_{N \in \mathbb{N}}$  converges uniformly on  $B(x_0, \gamma^*(\omega)) \cap K_d$ . Therefore, its limit  $S$  is continuous on  $B(x_0, \gamma^*(\omega)) \cap K_d$ . Moreover, letting  $N \rightarrow +\infty$  in (30) (which holds since  $\omega \in \tilde{\Omega}$ ), we get

$$|S(x) - S(y)| \leq C(1 + 2\tilde{C})F(3\kappa^2\rho(x, y)), \quad (31)$$

for every  $x, y \in B(x_0, \gamma^*(\omega)) \cap K_d$ , which concludes the proof.  $\square$

Let us now prove Lemma B.1.

**Proof of Lemma B.1..** Let us first observe that  $x^{(n)} = x \in B(x_0, \gamma(\omega)) \cap K_d$  and  $y^{(n)} = y \in B(x_0, \gamma(\omega)) \cap K_d$ . Let us now fix  $j \in \{k, \dots, n-1\}$ . The lower bound of Equation (7) leads to

$$\|x^{(j)} - x_0\| \leq \|x^{(j)} - x\| + \|x - x_0\| \leq \frac{\rho(x^{(j)}, x)^{1/\bar{H}}}{c_{2,1}^{1/\bar{H}}} + \|x - x_0\|.$$

Since  $x \in B(x_0, \gamma^*(\omega))$  with  $\gamma^*$  satisfying Equation (26) and since  $\rho(x^{(j)}, x) \leq 2^{-j}$  with  $j \geq k \geq k^*(\omega)$ ,

$$\|x^{(j)} - x_0\| \leq \frac{2^{-k^*(\omega)/\bar{H}}}{c_{2,1}^{1/\bar{H}}} + \frac{\gamma(\omega)}{2}.$$

Then, choosing  $k^*(\omega)$  large enough,  $x^{(j)} \in B(x_0, \gamma(\omega))$  for  $j = k, \dots, n-1$ . The same holds for  $y^{(j)}$ . Assertion 1. is then proved.

Let us now observe that since  $j \geq k_0$  and since  $\kappa \geq 1$ ,

$$2^j \delta_{j+1} \geq 2^{k_0} \delta_{k_0+1} > 3\kappa^2 \geq 3\kappa \quad (32)$$

by definition of  $k_0$  (see the third step of the proof of Theorem 3.1). Then, using the quasi-triangle inequality fulfilled by  $\rho$  and (28), we obtain that

$$\rho(x^{(j+1)}, x^{(j)}) \leq 3\kappa 2^{-(j+1)} \leq \frac{\delta_{j+1}}{2} \leq \delta_{j+1}.$$

Since the same holds for  $\rho(y^{(j+1)}, y^{(j)})$ , Assertion 2. is fulfilled. Moreover, applying twice the quasi-triangle inequality fulfilled by  $\rho$  and Equations (27), (28) and (32) (with  $j = k$ ), we obtain

$$\rho(x^{(k)}, y^{(k)}) \leq \kappa^2(2^{1-k} + \rho(x, y)) \leq 3\kappa^2 \rho(x, y) \leq \delta_k,$$

which is Assertion 3.  $\square$

Let us now focus on Corollary 3.2. Its proof is based on the following technical lemma.

**Lemma B.2.** *Let  $K_d = \prod_{i=1}^d [a_i, b_i] \subset \mathbb{R}^d$  be a compact  $d$ -dimensional interval,  $\beta \in (0, 1)$ ,  $\eta \in \mathbb{R}$  and  $\rho$  be a quasi-metric on  $\mathbb{R}^d$  satisfying Equation (7). Let  $(f_n)_{n \in \mathbb{N}}$  be a sequence of functions defined on  $K_d$  and let  $(\mathring{B}(x_i, r_i))_{1 \leq i \leq p}$  be a finite covering of  $K_d$  by open balls with  $x_i \in K_d$  and  $r_i > 0$ . Assume that for each  $1 \leq i \leq p$ , there exists a finite positive constant  $C_i$  such that*

$$\forall x, y \in \mathring{B}(x_i, r_i) \cap K_d, \sup_{n \in \mathbb{N}} |f_n(x) - f_n(y)| \leq C_i \rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta.$$

Then there exists a finite positive constant  $C$  such that

$$\forall x, y \in K_d, \sup_{n \in \mathbb{N}} |f_n(x) - f_n(y)| \leq C \rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta. \quad (33)$$

**Proof.** By the Lebesgue's number lemma, there exists  $r > 0$  such that

$$\forall x \in K_d, \exists 1 \leq i \leq p, \mathring{B}(x, r) \subset \mathring{B}(x_i, r_i).$$

Let us first note that since the map  $F_\rho : (u, v) \mapsto \rho^\beta(u, v) [\log(1 + \rho(u, v)^{-1})]^\eta$  is positive and continuous on the compact set  $\tilde{K} = \{(u, v) \in K \times K / \|u - v\| \geq r\}$ ,

$$m := \inf_{\tilde{K}} F_\rho \in (0, +\infty).$$

Then distinguishing the cases  $\|x - y\| < r$  and  $\|x - y\| \geq r$ , one easily sees that

$$\sup_{n \in \mathbb{N}} |f_n(x) - f_n(y)| \leq \max \left( \max_{1 \leq i \leq p} C_i, \frac{M}{m} \right) \rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta$$

where  $M = \sup_{n \in \mathbb{N}} \sup_{x, y \in K_d} |f_n(x) - f_n(y)|$ . It remains to prove that  $M < +\infty$ . Note that

$$\sup_{\substack{x, y \in K_d \\ \|x - y\| < r}} |f_n(x) - f_n(y)| \leq c \max_{1 \leq i \leq p} C_i$$

where  $c = \sup_{K_d \times K_d} F_\rho < +\infty$  by continuity of  $F_\rho$  on the compact set  $K_d \times K_d$ . Then since  $K_d$  is a compact convex set, using a chaining argument, one easily obtains that  $M < +\infty$ , which concludes the proof.  $\square$

**Proof of Corollary 3.2.** We only prove Assertion 1. Actually, Assertion 2. is proved using the same arguments but replacing  $K_d$  by  $B(x_0, \gamma) \cap K_d$ .

Assume that for any  $x_0 \in K_d$ , Assumption 2 holds with  $\Omega'$ ,  $\beta$ ,  $\eta$  and the quasi-metric  $\rho$  independent of  $x_0$ . Following the proof of Theorem 3.1 and keeping its notation, let us quote that  $\gamma^*$  and  $\tilde{\Omega}$  do not depend on  $x_0$ . Let us now fix  $\omega \in \tilde{\Omega}$ . From the third step of the proof of Theorem 3.1 and Lemma B.2, we deduce that Equation (30) still hold for any  $x, y \in K_d$ . This allows to replace  $B(x_0, \gamma^*(\omega))$  by  $K_d$  in the fourth step of the proof of Theorem 3.1, which leads to Assertion 1.  $\square$

## B.2. Rate of almost sure uniform convergence

**Proof of Theorem B.2.** Let us first observe that Theorem 3.1 holds. Then, for almost  $\omega$ , even if it means to choose  $\gamma$  smaller, the sequence of continuous functions  $(S_N(\cdot)(\omega))_{N \in \mathbb{N}}$  converges uniformly on  $B(x_0, \gamma(\omega)) \cap K_d$ , which implies that each  $R_N(\cdot)(\omega)$  is continuous on  $B(x_0, \gamma(\omega)) \cap K_d$ . As in the proof of Theorem 3.1, we assume without loss of generality that  $K_d = \prod_{j=1}^d [a_j, b_j]$  with  $a_j < b_j$ .

**Proof of Assertion 1.** Since it is quite similar to the proof of Equation (30), we only sketch it.

For  $k \in \mathbb{N} \setminus \{0\}$ ,  $N \in \mathbb{N}$  and  $(i, j) \in \mathbb{Z}^d$ , we consider

$$E_{i,j}^{k,N} = \left\{ \omega : |R_N(x_{\nu_k,i}) - R_N(x_{\nu_k,j})| > \sqrt{\log(N+2)} r_N(x_{\nu_k,i}, x_{\nu_k,j}) \varphi(\rho(x_{\nu_k,i}, x_{\nu_k,j})) \right\}$$

with  $r_N$  defined by (9),  $\varphi$  by (23) and  $(\nu_k)_{k \geq 1}$  by Step 1 of the proof of Theorem 3.1. Then, we proceed as in Step 1 of the proof of Theorem 3.1 replacing the set  $E_k$  by

$$E'_k = \bigcup_{N=0}^{+\infty} \bigcup_{(i,j) \in I_k} E_{i,j}^{k,N},$$

with  $I_k$  and  $\delta_k$  defined by (24), and applying Assertion 2. of Proposition 2.1 instead of Assertion 1. Then, choosing the constant  $A$ , which appears in the definition of  $\varphi$ , and  $\delta \in (0, 1)$  such that

$$A(1-\delta) - \frac{2}{\underline{H}} + \frac{1-\delta}{\overline{H}} > 0 \quad \text{and} \quad A(1-\delta) \log 2 > 1$$

we obtain that

$$\sum_{k=1}^{+\infty} \mathbb{P}(E'_k) \leq c_2 \sum_{N=2}^{+\infty} 2^{-A(1-\delta) \log N} = c_2 \sum_{N=2}^{+\infty} N^{-A(1-\delta) \log 2} < +\infty$$

with  $c_2$  a finite positive constant. Then, by Borel-Cantelli Lemma, the definition of  $\varphi$  and Assumption 3, almost surely there exists an integer  $k^*(\omega)$  such that for every  $k \geq k^*(\omega)$ , for all  $N \in \mathbb{N}$ , and for all  $x, y \in \mathcal{D}_{\nu_k}$  with  $x, y \in B(x_0, \gamma(\omega)) \cap K_d$  and  $\rho(x, y) \leq \delta_k = 2^{-(1-\delta)k}$

$$|R_N(x) - R_N(y)| \leq Cb(N) \sqrt{\log(N+2)} \rho(x, y)^\beta |\log(\rho(x, y))|^{\eta+1/2}.$$

In addition, replacing in Step 2 of the proof of Theorem 3.1,  $S_N$  by  $R_N$  (which still be, for almost  $\omega$ , continuous on  $B(x_0, \gamma(\omega)) \cap K_d$ ), we obtain that for almost  $\omega$ , there exists  $\gamma^* \in (0, \gamma)$ , such that

$$|R_N(x) - R_N(y)| \leq Cb(N) \sqrt{\log(N+2)} \rho(x, y)^\beta |\log(\rho(x, y))|^{\eta+1/2} \quad (34)$$

for every  $N \in \mathbb{N}$  and  $x, y \in B(x_0, \gamma^*(\omega)) \cap K_d$ . This establishes Assertion 1.

**Proof of Assertion 2.** This assertion follows from Equations (34) and (11), the continuity of  $\rho$  on the compact set  $B(x_0, \gamma(\omega)) \cap K_d$  and

$$|R_N(x)| \leq |R_N(x) - R_N(x_0)| + |R_N(x_0)|.$$

The proof of Theorem 3.3 is then complete.  $\square$

**Proof of Corollary 3.4.** We only prove Assertion 1. Actually, Assertion 2. is proved using the same arguments but replacing  $K_d$  by  $B(x_0, \gamma) \cap K_d$ .

Let us assume that Assumption 3 holds with  $\Omega', \beta, \eta$  and the quasi-metric  $\rho$  independent of  $x_0$ . Note first that the almost sure event  $\tilde{\Omega}$  under which (34) holds does not depend on  $x_0$ . Then applying Lemma B.2 to  $f_n = R_n / (b(n)\sqrt{\log(n+2)})$ , we obtain that Equation (34) still holds for  $x, y \in K_d$ . If moreover for some  $x_0$ , Equation (11) is fulfilled, then following the proof of Assertion 2. of Theorem 3.3, we also have: there exists  $C$  a finite positive random variable such that for all  $N \in \mathbb{N}$ ,

$$\sup_{x \in K_d} |R_N(x)| \leq Cb(N)\sqrt{\log(N+2)},$$

which concludes the proof.  $\square$

## Appendix C: Shot noise series

### C.1. Proof of Theorem 4.1

Let  $(g_n)_{n \geq 1}$  be a Rademacher sequence, that is a sequence of i.i.d. random variables with symmetric Bernoulli distribution. This Rademacher sequence is assumed to be independent of  $(T_n, X_n)_{n \geq 1}$ . Then, by independence and also by symmetry of the sequence  $(X_n)_{n \geq 1}$ ,  $(X_n g_n)_{n \geq 1}$  has the same distribution as  $(X_n)_{n \geq 1}$  and is independent of the sequence  $(T_n)_{n \geq 1}$ .

Let us now set

$$W_n(\alpha) = T_n^{-1/\alpha} X_n \quad \text{and} \quad S_N(\alpha) = \sum_{n=1}^N W_n(\alpha) g_n,$$

so that  $\{S_N^*(\alpha), N \geq 1\}$  has the same finite distribution as  $\{S_N(\alpha), N \geq 1\}$ . Moreover, since

$$\sum_{n=1}^N |W_n(\alpha)|^2 = \sum_{n=1}^N T_n^{-2/\alpha} |X_n|^2$$

with  $X_n \in L^{2p}$  (with  $p > 0$ ), Assumption 1 is fulfilled on any  $K_1 = [a, b] \subset (0, \min(2, 2p))$  (see e.g. Samorodnitsky and Taqqu (1994)).

Let us now fix  $a, b \in (0, \min(2, 2p))$  such that  $a < b$ ,  $a' \in (0, a)$  and  $b' \in (b, \min(2, 2p))$ . **Proof of Assertion 1.** By the Mean Value Inequality, we get that for any  $\alpha, \alpha' \in [a, b]$  and  $n \geq 1$ ,

$$\left| T_n^{-1/\alpha} - T_n^{-1/\alpha'} \right| \leq c|\alpha - \alpha'| \max \left( T_n^{-1/b'}, T_n^{-1/a'} \right) \quad (35)$$

with  $c$  a finite positive constant. It follows that, almost surely, for all  $\alpha, \alpha' \in [a, b]$ ,

$$s(\alpha, \alpha') := \left( \sum_{n=1}^{+\infty} |W_n(\alpha) - W_n(\alpha')|^2 \right)^{1/2} \leq C|\alpha - \alpha'|, \quad (36)$$

with  $C = c \left( \sum_{n=1}^{+\infty} T_n^{-2/b'} |X_n|^2 + \sum_{n=1}^{+\infty} T_n^{-2/a'} |X_n|^2 \right)^{1/2} < +\infty$  since  $|X_n|^2 \in L^p$  with  $2p > b' \geq a'$  and  $a', b' \in (0, 2)$ . Therefore, the assumptions of Assertion 1. of Corollary 3.2 hold. Let us now remark that for all  $\alpha, \alpha' \in [a, b]$ ,

$$\{(S_N^*(\alpha) - S_N^*(\alpha'), s(\alpha, \alpha')); N \geq 1\} \stackrel{fdd}{=} \{(S_N(\alpha) - S_N(\alpha'), s(\alpha, \alpha')); N \geq 1\}.$$

This allows us to replace  $S_N$  by  $S_N^*$  in the Second Step of the proof of Theorem 3.1. Then, the third and the fourth step of this proof still hold replacing  $S_N$  by  $S_N^*$  and the limit  $S$  by the limit  $S^*$  since each  $S_N^*$  is continuous (as  $S_N$  is) and since  $S_N^*$  converges pointwise to  $S^*$ . This allows us to also replace  $(S_N, S)$  by  $(S_N^*, S^*)$  in the proof of Assertion 1. of Corollary 3.2. It follows that almost surely,  $(S_N^*)_{N \in \mathbb{N}}$  converges uniformly on  $[a, b]$  to  $S^*$ . Since this holds for any  $0 < a < b < \min(2, 2p)$ , Assertion 1. of Theorem 4.1 is established.

**Proof of Assertion 2.** Since almost surely the sequence of continuous random fields  $(S_N^*)_{N \in \mathbb{N}}$  converges uniformly on  $[a, b]$ , for all  $N \in \mathbb{N}$  the rest  $R_N^*$ , defined by

$$R_N^*(\alpha) := \sum_{n=N+1}^{+\infty} T_n^{-1/\alpha} X_n,$$

is also continuous on  $[a, b]$ . Remark also that we have, for all  $\alpha, \alpha' \in [a, b]$  and  $N \in \mathbb{N}$ ,

$$(R_N^*(\alpha) - R_N^*(\alpha'), r_N(\alpha, \alpha')) \stackrel{d}{=} (R_N(\alpha) - R_N(\alpha'), r_N(\alpha, \alpha')),$$

where  $R_N(\alpha) = \sum_{n=N+1}^{+\infty} T_n^{-1/\alpha} X_n g_n = S(\alpha) - S_N(\alpha)$  and

$$r_N(\alpha, \alpha') = \left( \sum_{n=N+1}^{+\infty} |X_n|^2 \left| T_n^{-1/\alpha} - T_n^{-1/\alpha'} \right|^2 \right)^{1/2}.$$

As done for  $S_N$ , the previous lines allow to replace  $R_N$  by  $R_N^*$  in the proof of Theorem 3.3. Moreover, by Equation (35), almost surely, for all  $N \in \mathbb{N}$ , and  $\alpha, \alpha' \in [a, b]$ ,

$$r_N(\alpha, \alpha') \leq c|\alpha - \alpha'| \left( \sum_{n=N+1}^{+\infty} T_n^{-2/b'} |X_n|^2 + \sum_{n=N+1}^{+\infty} T_n^{-2/a'} |X_n|^2 \right)^{1/2}. \quad (37)$$



Let us now fix  $p' > 0$  such that  $1/p' \in (0, 1/b - 1/\min(2p, 2))$ . Choosing if necessary  $b' > b$  smaller, we assume without loss of generality that  $1/p' \in (0, 1/b' - 1/\min(2p, 2)) \subset (0, 1/a' - 1/\min(2p, 2))$ . Then, by Theorem 2.2 in [Cohen et al. \(2008\)](#), almost surely, for all  $\alpha, \alpha' \in [a, b]$ ,

$$\sup_{N \in \mathbb{N}} N^{2/p'} \left( \sum_{n=N+1}^{+\infty} T_n^{-2/b'} |X_n|^2 + \sum_{n=N+1}^{+\infty} T_n^{-2/a'} |X_n|^2 \right) < +\infty$$

since  $X_n^2 \in L^p$  with  $p > b'/2 > a'/2$  and  $a', b' \in (0, 2)$ . Note also that by Theorem 2.1 in [Cohen et al. \(2008\)](#), for all  $x_0 = \alpha_0 \in [a, b]$ , almost surely

$$\sup_{N \in \mathbb{N}} N^{1/p'} \left| \sum_{n=N+1}^{+\infty} T_n^{-1/\alpha_0} X_n \right| < +\infty.$$

Therefore, the assumptions of Assertion 1. of Corollary 3.2 hold with  $b(N) = (N+1)^{-1/p'}$  for any  $p'$  such that  $1/p' \in (0, 1/b - 1/\min(2p, 2))$ . And then, substituting in its proof  $R_N$  by  $R_N^*$ , almost surely

$$\sup_{N \in \mathbb{N}} \sup_{\alpha \in [a, b]} N^{1/p'} |R_N^*(\alpha)| < +\infty,$$

which concludes the proof.  $\square$

## C.2. Modulus of continuity and rate of convergence

This section is devoted to the proofs of the results stated in Section 4.2. First, let us establish Theorem 4.2.

**Proof of Theorem 4.2.** Let us fix  $x_0 = (\alpha_0, u_0) \in K_{d+1} = [a, b] \times \prod_{j=1}^d [a_j, b_j] \subset (0, 2) \times \mathbb{R}^d$ .

**Proof of Assertion 1.** Let us assume that  $p > b/2$  and consider  $s$  the conditional parameter defined by (6). Then, for any  $x = (\alpha, u) \in K_{d+1}$  and  $y = (\alpha', v) \in K_{d+1}$ ,

$$s(x, y) \leq s_1(x, y) + s_2(x, y), \quad (38)$$

where

$$s_1(x, y) = \left( \sum_{n=1}^{+\infty} T_n^{-2/\alpha} |V_n(x) - V_n(y)|^2 \right)^{1/2} \quad \text{and} \quad s_2(x, y) = \left( \sum_{n=1}^{+\infty} \left( T_n^{-1/\alpha} - T_n^{-1/\alpha'} \right)^2 |V_n(y)|^2 \right)^{1/2}.$$

First, let us focus on  $s_1$ . Note that for any  $x, y \in K_{d+1}$ ,

$$s_1(x, y) \leq C_1 \rho(x, y)^\beta \log(1 + \rho(x, y)^{-1})^\eta,$$

with  $C_1 = \left( \sum_{n=1}^{+\infty} T_n^{-2/b} |Y_n|^2 + \sum_{n=1}^{+\infty} T_n^{-2/a} |Y_n|^2 \right)^{1/2}$ , where we have set

$$Y_n = \sup_{\substack{x, y \in K_{d+1} \\ x \neq y}} \frac{|V_n(x) - V_n(y)|}{\rho(x, y)^\beta \log(1 + \rho(x, y)^{-1})^\eta}.$$

Since  $K_d$  is a convex compact set, applying a chaining argument and using the continuity of  $\rho$ , one checks that Equation (13) implies that  $Y_n \in L^{2p}$ . Then, since  $2p > b \geq a$  and since the random variables  $Y_n$ ,  $n \geq 1$ , are i.i.d, Theorem 1.4.5 of [Samorodnitsky and Taqqu \(1994\)](#) ensures that  $C_1 < +\infty$  almost surely.

Let us now focus on  $s_2$ . Observe that  $|V_n(y)| \leq X_n$ , with

$$X_n = |V_n(x_0)| + c_1 Y_n$$

for  $c_1 = \sup_{z \in K_{d+1}} \rho(x_0, z)^\beta |\log(1 + \rho(x_0, z)^{-1})|^\eta$ . Let us remark that  $c_1 < +\infty$ , by continuity of  $\rho$  on the compact set  $\{x_0\} \times K_{d+1}$ . Moreover, since  $V_n(x_0) \in L^{2p}$ ,  $(X_n)_{n \geq 1}$  is still a sequence of i.i.d. variables in  $L^{2p}$  and following the same lines as for Equation (36), we obtain that, almost surely, for any  $x, y \in K_{d+1}$ ,

$$s_2(x, y) \leq C_2 |\alpha - \alpha'|$$

with  $C_2$  a finite positive random variable. Let us also note that by Equation (8), there exist finite positive constants  $c_2$  and  $c_3$  such that for any  $x = (\alpha, u) \in K_{d+1}$  and any  $y = (\alpha', v) \in K_{d+1}$ ,

$$|\alpha - \alpha'| \leq c_2 \rho(x, y)^{1/\overline{H}} \leq c_3 \rho(x, y)$$

since  $\overline{H} \leq 1$ . Hence, since  $\beta \in (0, 1]$ , almost surely, for any  $x, y \in K_{d+1}$ ,

$$s(x, y) \leq C \rho(x, y)^\beta \log(1 + \rho(x, y)^{-1})^{\max(\eta, 0)}$$

with  $C$  a finite positive random variable. Then Assertion 1. follows from Corollary 3.2.

**Proof of Assertion 2.** Let us choose  $p' > 0$  such that  $1/p' \in (0, 1/b - 1/\min(2, 2p))$ . Then, replacing in the previous lines  $s$  by the parameter  $r_N$  and Theorem 1.4.5 of [Samorodnitsky and Taqqu \(1994\)](#) by Theorem 2.2 of [Cohen et al. \(2008\)](#), we obtain: there exists  $C$  a finite positive random variable such that almost surely, for any  $x, y \in K_{d+1}$ , and for any  $N \in \mathbb{N}$ ,

$$r_N(x, y) \leq C(N+1)^{-1/p'} \rho(x, y)^\beta \log(1 + \rho(x, y)^{-1})^{\max(\eta, 0)}.$$

Note also that by Theorem 2.1 in [Cohen et al. \(2008\)](#), almost surely

$$\sup_{N \in \mathbb{N}} N^{1/p'} |R_N(x_0)| < +\infty.$$

Therefore, by Corollary 3.4, almost surely,

$$\sup_{N \in \mathbb{N}} N^{1/p'} \sup_{x \in K_{d+1}} |R_N(x)| < +\infty,$$

which concludes the proof.  $\square$

Let us now prove Proposition 4.3.

**Proof of Proposition 4.3.** Since Equation (7) is fulfilled, there exists  $r \in (0, 1)$  such that  $\rho(x, y) \leq h_0$  for all  $x, y \in K_{d+1}$  with  $\|x - y\| \leq r$ . Then, the assumptions done imply that

$$X_1 := \sup_{\substack{x, y \in K_{d+1} \\ 0 < \|x - y\| \leq r}} \frac{|V_1(x) - V_1(y)|}{\rho(x, y)^\beta |\log \rho(x, y)|^\eta} \leq \sup_{h \in (0, h_0]} \frac{\mathcal{G}(h)}{F(h)} := G$$

where  $F(h) := h^\beta |\log h|^\eta$ . We assume without loss of generality that  $h_0 = 2^{-k_0}$  with an integer  $k_0 \geq 1$  is such that  $F$  is increasing on  $(0, h_0]$  and Equation (14) holds for  $h \in (0, h_0]$ . Then, using the monotonicity of  $\mathcal{G}$  and  $F$ ,

$$G^{2p} \leq \sum_{k=k_0}^{+\infty} \sup_{h \in (2^{-k-1}, 2^{-k}]} \left( \frac{\mathcal{G}(h)}{F(h)} \right)^{2p} \leq \max(2^\eta, 1)^{2p} \sum_{k=k_0}^{+\infty} \left( \frac{\mathcal{G}(2^{-k})}{F(2^{-k})} \right)^{2p}.$$

Therefore, by Equation (14) and definition of  $F$ ,

$$\mathbb{E}(X_1^{2p}) \leq \mathbb{E}(G^{2p}) \leq \max(2^\eta, 1)^{2p} \sum_{k=k_0}^{+\infty} |k \log 2|^{-1-2p\varepsilon} < +\infty,$$

which concludes the proof.  $\square$

### C.3. Proof of Proposition 4.4

Let  $K_{d+1} = [a, b] \times \prod_{j=1}^d [a_j, b_j] \subset (0, 2) \times \mathbb{R}^d$ .

**Proof of Assertion 1.** Let us fix an integer  $p \geq 1$  and consider  $x^{(j)} = (\alpha_j, u^{(j)}) \in K_{d+1}$  for each integer  $1 \leq j \leq p$ . Then, we set  $\vec{x} = (x^{(1)}, \dots, x^{(p)})$ . Choosing  $\mathcal{S} = \{\xi \in \mathbb{R}^d; m(\xi) > 0\}$  we define  $H_{\vec{x}} : (0, +\infty) \times \mathcal{S} \times \mathbb{C} \rightarrow \mathbb{C}^p$  by

$$H_{\vec{x}}(r, \xi, g) = \left( r^{-1/\alpha_1} f_{\alpha_1}(u^{(1)}, \xi) m(\xi)^{-1/\alpha_1} g, \dots, r^{-1/\alpha_p} f_{\alpha_p}(u^{(p)}, \xi) m(\xi)^{-1/\alpha_p} g \right). \quad (39)$$

Let us note that almost surely

$$\sum_{n=1}^N H_{\vec{x}}(T_n, \xi_n, g_n) = \left( S_{m,N}(x^{(1)}), \dots, S_m(x^{(p)}) \right)$$

where  $S_{m,N}$  is defined by (4) with  $W_n$  given by (12). Then this series converges almost surely to  $(S_m(x^{(1)}), \dots, S_m(x^{(p)}))$ . Since  $g_1$  is symmetric, applying Theorem 2.4 of Rosiński (1990) and using a simple change of variables ( $t = rm(\xi)$ ) and  $\nu(\mathbb{R}^d \setminus \mathcal{S}) = 0$ , we obtain that

$$\forall \lambda = (\lambda_1, \dots, \lambda_p) \in \mathbb{C}^p, \forall z \in \mathbb{C}, \mathbb{E} \left( e^{i\Re(\bar{z} \sum_{j=1}^p \lambda_j S_m(x^{(j)}))} \right) = \exp(I_{\vec{x}, \lambda}(z))$$

where

$$I_{\vec{x},\lambda}(z) = \int_{(0,+\infty) \times \mathbb{R}^d \times \mathbb{C}} \left( e^{i\Re(\bar{z}\langle \lambda, J_{\vec{x}}(t, (\xi, g)) \rangle)} - 1 - i\Re(\bar{z}\langle \lambda, J_{\vec{x}}(t, (\xi, g)) \rangle) \mathbf{1}_{|\Re(\bar{z}\langle \lambda, J_{\vec{x}}(t, (\xi, g)) \rangle)| \leq 1} \right) dt \nu(d\xi) \mathbb{P}_g(dg)$$

with  $\mathbb{P}_g$  the distribution of  $g_1$  and

$$J_{\vec{x}}(t, (\xi, g)) = \left( t^{-1/\alpha_1} f_{\alpha_1}(u^{(1)}, \xi) g, \dots, t^{-1/\alpha_p} f_{\alpha_p}(u^{(p)}, \xi) g \right).$$

Therefore,  $I_{\vec{x},\lambda}$  does not depend on the function  $m$ , and then neither does the distribution of the vector  $(S_m(x^{(1)}), \dots, S_m(x^{(p)}))$ . Since this holds for any  $p$  and  $\vec{x}$ , Assertion 1. is established.

**Proof of Assertion 2.** Let us now consider the space  $B = \mathcal{C}(K_{d+1}, \mathbb{C})$  of complex-valued continuous functions defined on the compact set  $K_{d+1}$ . This space is endowed with the topology of the uniform convergence, so that it is a Banach space.

Let us assume that  $S_{\tilde{m}}$  belongs almost surely to  $\mathcal{H}_\rho(K_{d+1}, \beta, \eta) \subset B$ . For any  $\vec{x} = (x^{(1)}, \dots, x^{(p)}) \in K_{d+1}^p$ , in view of its characteristic function, the vector  $(S_{\tilde{m}}(x^{(1)}), \dots, S_{\tilde{m}}(x^{(p)}))$  is infinitely divisible and its Lévy measure is given by

$$F_{\vec{x}}(A) = \int_{(0,+\infty) \times \mathcal{S} \times \mathbb{C}} \mathbf{1}_{A \setminus \{0\}}(H_{\vec{x}}(r, \xi, g)) m(\xi) dr \nu(d\xi) \mathbb{P}_g(dg)$$

for any Borel set  $A \in \mathcal{B}(B)$ . We first assume that  $(\alpha, u) \mapsto f_\alpha(u, \xi)$  belongs to  $B$  for all  $\xi \in \mathbb{R}^d$  so that the function

$$\begin{aligned} H : (0, +\infty) \times \mathcal{S} \times \mathbb{C} &\longrightarrow B \\ (r, \xi, g) &\longmapsto \left( (\alpha, u) \mapsto r^{-1/\alpha} f_\alpha(u, \xi) m(\xi)^{-1/\alpha} \right) \end{aligned}$$

is well-defined. Since  $H_{\vec{x}}$  is defined by (39), one checks that  $(S_{\tilde{m}}(x))_{x \in K_{d+1}}$  is a  $B$ -valued infinitely divisible random variable with Lévy measure defined by

$$F(A) = \int_{(0,+\infty) \times \mathcal{S} \times \mathbb{C}} \mathbf{1}_{A \setminus \{0\}}(H(r, \xi, g)) m(\xi) dr \nu(d\xi) \mathbb{P}_g(dg), \quad A \in \mathcal{B}(B).$$

Then, by Theorem 2.4 of Rosiński (1990),  $\sum_{n=1}^N H(T_n, (\xi_n, g_n))$  converges almost surely in  $B$  as  $N \rightarrow +\infty$ . Then, by definition of  $H$ , the sequence  $(S_{m,N})_{N \in \mathbb{N}}$  converges in  $B$  almost surely. Therefore, its limit  $S_m$  is almost surely continuous on  $K_{d+1}$ .

Let us now consider  $\mathcal{D} \subset K_{d+1}$  a countable dense set in  $K_{d+1}$ . Then, since almost surely  $S_{\tilde{m}} \in \mathcal{H}_\rho(K_{d+1}, \beta, \eta)$  and since  $S_m \stackrel{fdd}{=} S_{\tilde{m}}$ , we get that almost surely

$$\sup_{\substack{x, y \in \mathcal{D} \\ x \neq y}} \frac{|S_m(x) - S_m(y)|}{\rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta} < +\infty.$$

Then, by continuity of  $\rho$ , by almost sure continuity of  $S_m$  and by density of  $\mathcal{D}$  on the compact set  $K_{d+1}$ ,

$$\sup_{\substack{x, y \in K_{d+1} \\ x \neq y}} \frac{|S_m(x) - S_m(y)|}{\rho(x, y)^\beta [\log(1 + \rho(x, y)^{-1})]^\eta} < +\infty$$

almost surely, that is  $S_m$  belongs almost surely to  $\mathcal{H}_\rho(K_{d+1}, \beta, \eta)$ . This establishes Assertion 2. when  $(\alpha, u) \mapsto f_\alpha(u, \xi)$  is continuous for all  $\xi \in \mathbb{R}^d$ .

Assume now that  $(\alpha, u) \mapsto f_\alpha(u, \xi)$  is continuous for  $\xi \in \mathbb{R}^d \setminus \mathcal{N}$  with  $\nu(\mathcal{N}) = 0$  and set

$$g_\alpha(u, \xi) := f_\alpha(u, \xi) \mathbf{1}_{\mathbb{R}^d \setminus \mathcal{N}}(\xi).$$

Then, almost surely, for all  $x = (\alpha, u) \in (0, 2) \times \mathbb{R}^d$  and all  $N \geq 1$ ,

$$S_{m,N}(x) = \sum_{n=1}^N T_n^{-1/\alpha} g_\alpha(u, \xi_n) m(\xi_n)^{-1/\alpha} g_n,$$

and the conclusion follows from the previous lines since  $(\alpha, u) \mapsto g_\alpha(u, \xi)$  is continuous on  $K_{d+1}$  for all  $\xi \in \mathbb{R}^d$ . The proof of Proposition 4.4 is then complete.  $\square$

## Appendix D: Applications

### D.1. Proof of Proposition 5.1

Let us first note that using Remark 5.1, we can and may assume without loss of generality that  $a_1 = 1$ , up to replace  $E$  by  $E/a_1$  and  $\tau_E$  by  $\tau_{E/a_1}^{1/a_1}$ .

Let us choose  $\zeta > 0$  arbitrarily small and consider the Borel function  $\tilde{m}$  defined on  $\mathbb{R}^d$  by

$$\tilde{m}(\xi) = \|\xi\|^{\alpha_0} \mathbf{1}_{\|\xi\| \leq A} + \tau_{E^t}(\xi)^{-q(E)} |\log \tau_{E^t}(\xi)|^{-1-\zeta} \mathbf{1}_{\|\xi\| > A}.$$

Observe that  $\tilde{m}$  is positive on  $\mathbb{R}^d \setminus \{0\}$ . Then,

$$0 < c = \int_{\mathbb{R}^d} \tilde{m}(\xi) d\xi = c_1 + c_2$$

with

$$c_1 = \int_{\|\xi\| \leq A} \|\xi\|^{\alpha_0} d\xi \quad \text{and} \quad c_2 = \int_{\|\xi\| > A} \tau_{E^t}(\xi)^{-q(E)} |\log \tau_{E^t}(\xi)|^{-1-\zeta} d\xi.$$

Let us first observe that  $c_1 < \infty$  since  $\alpha_0 > 0$ . To prove that  $c_2$  is also a finite constant, we need some tools given in Meerschaert and Scheffler (2001); Biermé et al. (2007). As

in Chapter 6 of [Meerschaert and Scheffler \(2001\)](#), let us consider the norm  $\|\cdot\|_{E^t}$  defined by

$$\|x\|_{E^t} = \int_0^1 \left\| \theta^{E^t} x \right\| \frac{d\theta}{\theta}, \quad \forall x \in \mathbb{R}^d. \quad (40)$$

According to the change of variables in polar coordinates (see [Biermé et al. \(2007\)](#)) there exists a finite positive Radon measure  $\sigma_{E^t}$  on  $S_{E^t} = \{\xi \in \mathbb{R}^d : \|\xi\|_{E^t} = 1\}$  such that for all measurable function  $\varphi$  non-negative or in  $L^1(\mathbb{R}^d, d\xi)$ ,

$$\int_{\mathbb{R}^d} \varphi(\xi) d\xi = \int_0^{+\infty} \int_{S_{E^t}} \varphi(r^{E^t} \theta) \sigma_{E^t}(d\theta) r^{q(E)-1} dr.$$

Applying this change of variables, it follows that  $c_2 < \infty$  since  $\zeta > 0$ . Hence,  $m = \tilde{m}/c$  is well-defined and  $\mu(d\xi) = m(\xi)d\xi$  is a probability measure equivalent to the Lebesgue measure. Then we may consider  $S_m(\alpha_0, u)$  defined by (15) for  $u \in \mathbb{R}^d$  so that  $X_{\alpha_0} \stackrel{fdd}{=} d_{\alpha_0} S_m(\alpha_0, \cdot)$  with  $d_{\alpha_0}$  given by (16).

To study the sample path regularity of  $S_m(\alpha_0, \cdot)$  on  $K_d = \prod_{j=1}^d [a_j, b_j]$ , we apply Proposition 4.3 on  $K_{d+1} = \{\alpha_0\} \times K_d \subset (0, 2) \times \mathbb{R}^d$  for

$$V_1(\alpha_0, u) = f_{\alpha_0}(u, \xi_1) m(\xi_1)^{-1/\alpha_0}$$

with  $f_{\alpha_0}$  defined by (18). We recall that here  $\xi_1$  is a random vector of  $\mathbb{R}^d$  with density  $m$ . Therefore let us now check that assumptions of Proposition 4.3 are fulfilled.

For  $h > 0$  and  $\xi \in \mathbb{R}^d$  we consider

$$g(h, \xi) = \min(c_{E^t} \|h^{E^t} \xi\|_{E^t}, 1) |\psi_{\alpha_0}(\xi)|,$$

where  $c_{E^t} > 0$  is chosen such that  $|e^{i\langle u, \xi \rangle} - 1| \leq c_{E^t} \|\tau_E(u)^{E^t} \xi\|_{E^t}$ . We consider the quasi-metric defined on  $\mathbb{R}^{d+1}$  by

$$\rho((\alpha, u), (\alpha', v)) = |\alpha - \alpha'| + \rho_E(u, v), \quad \forall (\alpha, u), (\alpha', v) \in \mathbb{R} \times \mathbb{R}^d,$$

which clearly satisfies Equation (7). By definition of  $V_1$ ,  $g$  and  $\|\cdot\|_{E^t}$ , the random field  $\mathcal{G} = (g(h, \xi_1))_{h \in [0, +\infty)}$  satisfies (i). and (ii). of Proposition 4.3. It remains to consider assumption (iii). Let

$$I(h) = \mathbb{E}(\mathcal{G}(h)^2) = \int_{\mathbb{R}^d} g(h, \xi)^2 m(\xi)^{1-2/\alpha_0} d\xi. \quad (41)$$

Since  $\psi_{\alpha_0}$  satisfies (19),

$$I(h) = \int_{\mathbb{R}^d} m(\xi)^{1-2/\alpha_0} \min\left(c_{E^t} \|h^{E^t} \xi\|_{E^t}, 1\right)^2 |\psi_{\alpha_0}(\xi)|^2 d\xi \leq I_1(h) + I_2(h)$$

with

$$I_1(h) = c^{2/\alpha_0-1} c_{E^t}^2 \int_{\|\xi\| \leq A} \left\| h^{E^t} \xi \right\|_{E^t}^2 \|\xi\|^{\alpha_0-2} |\psi_{\alpha_0}(\xi)|^2 d\xi,$$

where  $A$  is given by the condition (19), and

$$I_2(h) = c^{2/\alpha_0-1} c_\psi \int_{\mathbb{R}^d} \min \left( c_{E^t} \left\| h^{E^t} \xi \right\|_{E^t}, 2 \right)^2 \tau_{E^t}(\xi)^{-q(E)-2\beta} |\log \tau_{E^t}(\xi)|^{(1+\zeta)(2/\alpha_0-1)} d\xi.$$

From Lemma 3.2 of Biermé and Lacaux (2009) there exists a finite constant  $C_1 > 0$  such that for all  $h \in (0, e^{-1}]$

$$I_1(h) \leq C_1 h^{2a_1} |\log(h)|^{2(d-1)}.$$

Moreover, using again the change of variables in polar coordinates, there exists a finite constant  $C_2 > 0$  such that for all  $h \in (0, e^{-1}]$ ,

$$I_2(h) \leq C_2 h^{2\beta} |\log(h)|^{(1+\zeta)(2/\alpha_0-1)}.$$

Since  $\beta < a_1$ , one find a finite constant  $C_3 > 0$  such that

$$I(h) \leq C_3 h^{2\beta} |\log(h)|^{2(1+\zeta)(1/\alpha_0-1/2)}. \quad (42)$$

Hence, assumption (iii). of Proposition 4.3 is also fulfilled and applying this proposition, it follows that (13) is satisfied with  $\beta$  and  $\eta = 1/\alpha_0 + \varepsilon$ , for all  $\varepsilon > 0$ . Then, by Theorem 4.2, almost surely  $S_m \in \mathcal{H}_\rho(K_{d+1}, \beta, 1/\alpha_0 + 1/2 + \varepsilon)$ . By definition of  $\rho$  and  $K_{d+1}$ , this means that

$$S_m(\alpha_0, \cdot) \in \mathcal{H}_{\rho_E}(K_d, \beta, 1/\alpha_0 + 1/2 + \varepsilon).$$

In particular,  $S_m(\alpha_0, \cdot)$  is continuous on  $K_d$ . Then, since  $d_{\alpha_0} S_m(\alpha_0, \cdot) \stackrel{fdd}{=} X_{\alpha_0}$ ,  $X_{\alpha_0}$  is stochastically continuous and almost surely

$$C := \sup_{u, v \in \mathcal{D}, u \neq v} \frac{|X_{\alpha_0}(u) - X_{\alpha_0}(v)|}{\tau_E(u-v)^\beta [\log(1 + \tau_E(u-v)^{-1})]^{1/\alpha_0+1/2+\varepsilon}} < +\infty,$$

where  $\mathcal{D} \subset K_d$  is a countable dense in  $K_d = \prod_{j=1}^d [a_j, b_j]$ . So let us write  $\Omega^*$  this event and let us define a modification of  $X_{\alpha_0}$  on  $K_d$ .

First, if  $\omega \notin \Omega^*$ , we set  $X_{\alpha_0}^*(u)(\omega) = 0$  for all  $u \in K_d$ . Let us now fix  $\omega \in \Omega^*$ . Then, we set

$$X_{\alpha_0}^*(u)(\omega) = X_{\alpha_0}(u)(\omega), \forall u \in \mathcal{D}.$$

Let us now consider  $u \in K_d$ . Then, there exists  $u^{(n)} \in \mathcal{D}$  such that  $\lim_{n \rightarrow +\infty} u^{(n)} = u$ . It follows that,

$$\left| X_{\alpha_0}^*(u^{(n)})(\omega) - X_{\alpha_0}^*(u^{(m)})(\omega) \right| \leq C(\omega) \tau_E(u^{(n)} - u^{(m)})^\beta \left[ \log(1 + \tau_E(u^{(n)} - u^{(m)})^{-1}) \right]^{1/\alpha_0+1/2+\varepsilon},$$

so that  $(X_{\alpha_0}^*(u^{(n)})(\omega))_n$  is a Cauchy sequence and hence converges. We set

$$X_{\alpha_0}^*(u)(\omega) = \lim_{n \rightarrow +\infty} X_{\alpha_0}^*(u^{(n)})(\omega).$$

Remark that this limit does not depend on the choice of  $(u^{(n)})_n$  and that  $X_{\alpha_0}^*(\cdot)(\omega)$  is then well-defined on  $K_d$ . Observe also that, by stochastic continuity of  $X_{\alpha_0}$ ,  $X_{\alpha_0}^*$  is a modification of  $X_{\alpha_0}$ . Moreover, by continuity of  $\tau_E$ ,

$$C(\omega) = \sup_{u,v \in K_d, u \neq v} \frac{|X_{\alpha_0}^*(u)(\omega) - X_{\alpha_0}^*(v)(\omega)|}{\tau_E(u-v)^\beta [\log(1 + \tau_E(u-v)^{-1})]^{1/\alpha_0 + 1/2 + \varepsilon}} < +\infty$$

for all  $\omega \in \Omega$  and  $X_{\alpha_0}^*$  is continuous on  $K_d$ . This concludes the proof.  $\square$

## D.2. Multistable random fields

This section is devoted to the proofs of the results stated in Section 5.2. Let us first establish Proposition 5.2.

**Proof of Proposition 5.2.** Since  $\tilde{\rho}$  satisfies Equation (7), so does  $\rho$ . Then, Assumptions of Theorem 4.2 are fulfilled, which implies that  $(S_{m,N})_{N \in \mathbb{N}}$  converges uniformly to  $S_m$  on  $K_{d+1} = [a, b] \times K_d$ . Therefore,  $(\tilde{S}_{m,N})_{N \in \mathbb{N}}$  converges uniformly to  $\tilde{S}_m$  on  $K_d$  since  $\tilde{S}_{m,N}(u) = S_{m,N}(\alpha(u), u)$  and  $\tilde{S}_m(u) = S_m(\alpha(u), u)$  and  $\alpha$  is continuous. Moreover, by Theorem 4.2 there exists a finite positive random variable  $C$  such that for any  $u, v \in K_d$ ,

$$\left| \tilde{S}_m(u) - \tilde{S}_m(v) \right| \leq C \rho(x(u), x(v))^\beta \left[ \log \left( 1 + \rho(x(u), x(v))^{-1} \right) \right]^{\max(\eta, 0) + 1/2}$$

where  $x(w) = (\alpha(w), w)$ . Moreover, by definition of  $\rho$  and since  $\alpha \in \mathcal{H}_{\tilde{\rho}}(K_d, 1, 0)$ , there exists a finite positive constant  $c_1$  such that

$$\forall u, v \in K_d, \rho(x(u), x(v)) \leq c_1 \tilde{\rho}(u, v).$$

Let us now recall that since  $\tilde{\rho}$  is continuous on the compact set  $K_d \times K_d$ ,  $M = \sup_{u,v \in K_d} \tilde{\rho}(u, v) < +\infty$ . Then, up to change  $C$ , for all  $u, v \in K_d$ ,

$$\left| \tilde{S}_m(u) - \tilde{S}_m(v) \right| \leq C \tilde{\rho}(u, v)^\beta \left[ \log \left( 1 + \tilde{\rho}(u, v)^{-1} \right) \right]^{\max(\eta, 0) + 1/2}$$

since  $h \mapsto h^\beta \log(1 + h^{-1})^{\max(\eta, 0) + 1/2}$  is increasing around 0 and bounded on  $[0, M]$ . Assertion 1. is then proved. Moreover, Assertion 2. is a direct consequence of Assertion 2. of Theorem 4.2. The proof is then complete.  $\square$

Let us conclude this paper by the proof of Corollary 5.3.

**Proof of Corollary 5.3.** Let  $K_d = \prod_{j=1}^d [a_j, b_j] \subset \mathbb{R}^d$  and  $u_0 \in K_d$ . Let us set

$$a = \min_{K_d} \alpha, \quad b = \max_{K_d} \alpha \quad \text{and} \quad K_{d+1} = [a, b] \times K_d \subset (0, 2) \times \mathbb{R}^d$$



Let us first note that Assumption 5 is fulfilled with  $K_1 = [a, b]$  and then  $\tilde{S}_m$  is well-defined. Let us now consider  $\rho_E$  and  $\tau_E$  as defined in Example 2.1. Then we set

$$\tilde{m}(\xi) = \frac{c_\zeta}{\tau_{E^t}(\xi)^{q(E)} |\log \tau_{E^t}(\xi)|^{1+\zeta}},$$

with  $\zeta > 0$  a parameter chosen arbitrarily small. Therefore, let us consider

$$\tilde{V}_n(\alpha, u) = f_\alpha(u, \tilde{\xi}_n) \tilde{m}(\tilde{\xi}_n)^{-1/\alpha}$$

where  $(\tilde{\xi}_n)_{n \geq 1}$  is a sequence of i.i.d. random variables with common distribution  $\tilde{\mu}(d\xi) = \tilde{m}(\xi)d\xi$ . The sequence  $(\tilde{\xi}_n)_{n \geq 1}$  is assumed to be independent from  $(T_n, g_n)_{n \geq 1}$ . Then, Assumption 4 is fulfilled. Moreover,

$$\left| \tilde{V}_n(\alpha, u) - \tilde{V}_n(\alpha', v) \right| \leq \left| \tilde{V}_n(\alpha, u) - \tilde{V}_n(\alpha, v) \right| + \left| \tilde{V}_n(\alpha, v) - \tilde{V}_n(\alpha', v) \right|.$$

Let us set

$$C_1 = \sup_{\substack{u, v \in K_d \\ 0 < \|u - v\| \leq r}} \sup_{\alpha \in [a, b]} \frac{\left| \tilde{V}_1(\alpha, u) - \tilde{V}_1(\alpha, v) \right|}{\rho_E(u, v) |\log \rho_E(u, v)|^\eta} \quad \text{and} \quad C_2 = \sup_{\substack{\alpha, \alpha' \in [a, b] \\ \alpha \neq \alpha'}} \sup_{u \in K_d} \frac{\left| \tilde{V}_1(\alpha, u) - \tilde{V}_1(\alpha', u) \right|}{|\alpha - \alpha'|}$$

where  $r > 0$  and the choice of  $\eta \in \mathbb{R}$  is given below. Then, for any  $x = (\alpha, u) \in K_{d+1}$  and any  $y = (\alpha', v) \in K_{d+1}$  such that  $\|x - y\| \leq r$ ,

$$\begin{aligned} \left| \tilde{V}_1(x) - \tilde{V}_1(y) \right| &\leq (C_1 + C_2)(\rho_E(u, v) |\log \rho_E(u, v)|^\eta + |\alpha - \alpha'|) \\ &\leq c_1(C_1 + C_2)\rho(x, y) |\log \rho(x, y)|^\eta \end{aligned}$$

where  $c_1 \in (0, +\infty)$  is a finite constant and  $\rho(x, y) = \rho_E(u, v) + |\alpha - \alpha'|$ . Then, to apply Assertion 1. of Proposition 5.2 with  $\tilde{\rho} = \rho_E$  and  $\beta = 1$ , it suffices to establish that  $C_1, C_2$  and  $\tilde{V}_1(\alpha(u_0), u_0) \in L^2$  (since  $b < 2$ ).

Let us first deal with  $\tilde{V}_1(\alpha(u_0), u_0)$ . Using polar coordinates associated with  $E^t$  (see Meerschaert and Scheffler (2001)),

$$\mathbb{E} \left( \left| \tilde{V}_1(\alpha(u_0), u_0) \right|^2 \right) \leq c_2 \int_0^{+\infty} \min \left( \left\| t^{E^t} \right\|, 1 \right)^2 t^{-3} |\log t|^{2(1+\zeta)/\alpha(u_0)-1} dt$$

with  $c_2 \in (0, +\infty)$ . Hence, Lemma 2.1 of Biermé et al. (2007) proves that  $V_1(\alpha(u_0), u_0) \in L^2$  for any choice of  $\zeta$ .

Let us now consider the random variable  $C_1$ . By homogeneity and continuity of  $\psi$ , there exists a finite positive constant  $c_3$  such that for any  $u, v \in K_d$ ,

$$\sup_{\alpha \in [a, b]} \left| \tilde{V}_1(\alpha, u) - \tilde{V}_1(\alpha, v) \right| \leq c_3 \left| e^{i\langle u-v, \tilde{\xi}_1 \rangle} - 1 \right| Z_1$$

with

$$Z_1 = \tau_{E^t}(\tilde{\xi}_1)^{-1} \max \left( \left| \log \tau_{E^t}(\tilde{\xi}_1) \right|^{(1+\zeta)/a}, \left| \log \tau_{E^t}(\tilde{\xi}_1) \right|^{(1+\zeta)/b} \right).$$

Combining the proofs of Propositions 4.3 and 5.1, we obtain that for any  $\varepsilon > 0$ , choosing  $r$  small enough,

$$\mathbb{E} \left( \left[ \sup_{\substack{u, v \in K_d \\ 0 < \|u-v\| \leq r}} \frac{|e^{i\langle u-v, \tilde{\xi}_1 \rangle} - 1| Z_1}{\rho_E(u, v) |\log \rho_E(u, v)|^{1/a+\varepsilon}} \right]^2 \right) < +\infty.$$

This implies that for any  $\varepsilon > 0$ ,  $C_1 \in L^2$  for  $\eta = 1/a + \varepsilon$  and  $\zeta$  well-chosen.

Let us now study  $C_2$ . Since  $K_d$  is a compact set, using polar coordinates and the Mean Value Theorem, we have

$$\sup_{v \in K_d} \left| \tilde{V}_1(\alpha, v) - \tilde{V}_1(\alpha', v) \right| \leq c_4 |\alpha - \alpha'| Z_2$$

with  $Z_2 = \min \left( \left\| \tau_{E^t}(\xi_n)^{E^t} \right\|, 1 \right) Z_1 |\log \tau_{E^t}(\xi_n) + c_5|$  and  $c_4$  and  $c_5$  two finite positive constants. Using polar coordinates, one checks that  $Z_2 \in L^2$ , which implies that  $C_2 \in L^2$ .

Therefore, for any  $\varepsilon > 0$ , Assumptions of Assertion 1. of Proposition 5.2 are fulfilled for a well-chosen  $\zeta$ . This implies that almost surely, for any  $\varepsilon > 0$ ,  $\tilde{S}_m \in \mathcal{H}_{\rho_E}(K_d, 1, 1/a + 1/\varepsilon)$  with  $a = \min_{K_d} \alpha$ . Hence, for any  $\varepsilon > 0$ ,  $\tilde{S}_m \in \mathcal{H}_{\rho_E, B(u_0, r)}(u_0, 1, 1/\alpha(u_0) + 1/2 + 1/\varepsilon)$  for  $r$  small enough. This concludes the proof.  $\square$

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