Research Statement

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1 Abstract

My research interests and contributions mostly are in the areas of prediction, estimation and hypotheses testing problems for second order discrete- or continuous-time stationary stochastic processes, and related analytical problems: Toeplitz and Wiener-Hopf operators, orthogonal polynomials on the unit circle and their continual analogs (Krein's functions), and approximations in weighted Lebesgue spaces. The basic problems are:

- *Parametric estimation* of unknown spectral parameters (approximation of the likelihood function, local asymptotic normality of families of Gaussian distributions).
- *Nonparametric estimation* of spectral functionals (construction of asymptotically efficient estimators, bounding the minimax risks of estimators).
- *Limit theorems* and the large deviation principle for Toeplitz type random quadratic forms and functionals.
- *Testing* of simple and composite hypotheses about the spectrum of stationary processes (goodness-of-fit tests).
- *Prediction* of discrete- and continuous-time stationary stochastic processes (asymptotic behavior of the prediction error: direct and inverse problems).
- *Asymptotic behavior* of Toeplitz and Fredholm determinants, and traces of products of truncated Toeplitz and Wiener-Hopf operators.

Statistical inferences for dependent data have attracted the attention of many mathematicians and statisticians, not only because of their great theoretical interest, but also because of applications in different fields of science. Many practical problems from astronomy, economy, finance, hydrology, statistical physics, etc., require investigation of the above stated problems.

2 Basic Contributions

1. The above stated problems were considered for the class of *Muckenhoupt processes*.
2. The local asymptotic normality property of families of Gaussian distributions is established, and proved that the Whittle statistics are unbiased, consistent, asymptotically normal and asymptotically efficient estimators for unknown spectral parameters.
3. It was proved that the *simple "plug-in"* statistic $\Phi(I_T)$, where $I_T = I_T(\lambda)$ is the periodogram of the underlying process $X(t)$ with an unknown spectral density $f(\lambda)$, is H- and IK-asymptotically efficient estimator for a linear functional $\Phi(f)$, while for a nonlinear smooth functional $\Phi(f)$ an H- and IK-asymptotically efficient estimator is the *non-simple "plug-in"* statistic $\Phi(\widehat{f}_T)$, where $\widehat{f}_T$ is a sequence of "undersmoothed" kernel estimators of the unknown spectral density $f(\lambda)$.

4. For different classes of smooth spectral densities (Hölder, Besov, Sobolev), the rate of decrease of the minimax risks of estimators of spectral functionals is studied, and exact asymptotic bounds for minimax mean square risks of estimators of linear functionals are obtained.
5. A goodness-of-fit test for composite hypothesis H_0 that the hypothetical spectral density of the underlying process $X(t)$ has the specified form is constructed, extending the Chernov and Lehmann well-known result for independent observations.
6. Sufficient (close to necessary) conditions in terms of spectral density and generating functions ensuring central limit theorems for standard normalized Toeplitz-type quadratic forms and functionals are obtained.
7. The Ibragimov-Giraitis-Surgailis conjecture that the finiteness of the asymptotic variance of a random quadratic form is sufficient for applicability of central limit theorem was rejected.
8. For prediction error δ_T the estimates $\delta_T = O(T^{-\gamma})$ and $\delta_T = o(T^{-\gamma})$, $\gamma > 0$ as $T \to \infty$ were obtained for classes of smooth spectral densities that can possess Muckenhoupt-type and/or polynomial singularities.
9. Versions of Szegö weak theorem on Toeplitz determinants were obtained.
10. Error orders for integral limit approximations to the traces of products of truncated Toeplitz operators and matrices generated by integrable real symmetric functions were obtained.

3 The Model

Statistical analysis of Gaussian stationary processes usually involves two type of conditions imposed on the spectral density $f(\lambda)$:

(a) Conditions of the first type control the singularities (zeros and poles) of the spectral density function $f(\lambda)$, and specify the dependence structure of the underlying stochastic process.

(b) Conditions of the second type refer to smoothness properties of the spectral density function.

Depending on the dependence structure, the stationary processes may display short, intermediate or long memory. Much of statistical inferences (parametric and non-parametric) is concerned with the short-memory stationary models, in which case the spectral density of the model is separated from zero and infinity. However, the data in many fields of science (e.g. in economics, engineering, finance, hydrology, etc.) occur in the form of a realization of a stationary process $X(t)$ with possibly unbounded or vanishing spectral density.

A *short memory* processes is a second order stationary processes possessing a covariance function $\rho(u)$ and a spectral density function $f(\lambda)$ which is bounded above and below, i.e.

$$0 < C_1 \le f(\lambda) \le C_2 < \infty,$$

where C_1 and C_2 are absolute constants. A typical example of short memory processes is the ARMA process whose covariance function $\rho(u)$ is exponentially bounded, i.e. $|\rho(k)| \le Cr^k, k = 1, 2, \dots,$ where $0 < C < \infty$ and $0 < r < 1$.

An *intermediate memory* processes is a second order stationary processes possessing a spectral density $f(\lambda)$ that tends to zero as $\lambda \to 0$, and covariance function $\rho(u)$ satisfying

$$\sum_{k=-\infty}^{\infty} |\rho(k)| < \infty \quad \text{with} \quad \sum_{k=-\infty}^{\infty} \rho(k) = 0.$$

A typical example of intermediate memory processes is a stationary process whose covariance function $\rho(u)$ satisfies the condition $\rho(k) \sim Ck^{\alpha}$ as $k \to \infty$, where $C \ne 0$ and $\alpha < -1$.

A *long memory* processes is a second order stationary processes with covariance function $\rho(u)$ satisfying

$$\sum_{k=-\infty}^{\infty} |\rho(k)| = \infty.$$

A typical example of long memory processes is a stationary process whose covariance function $\rho(u)$ satisfies the condition $\rho(k) \sim Ck^{\alpha}$ as $k \to \infty$, where $C > 0$ and $-1 < \alpha < 0$.
Another well-known example of discrete-time long memory processes, which appears in many applied problems is a $FARIMA(p,d,q)$ process whose spectral density $f(\lambda)$ is given by

$$f(\lambda) = |1 - e^{i\lambda}|^{-2d} h(\lambda), \qquad 0 < d < 1/2,$$

where $h(\lambda)$ is the spectral density of an $ARMA(p,q)$ process.

In the continuous context, a basic process which has commonly been used to model long-range dependence is fractional Brownian motion (fBm) B_H with Hurst index H. This is a Gaussian process which has stationary increments and spectral density of the form

$$f(\lambda) = \frac{c}{|\lambda|^{2H+1}}, \quad c > 0, \quad 0 < H < 1, \quad \lambda \in \mathbb{R}, \tag{1}$$

where the form (1) can be understood in the sense of time-scale analysis, or in a limiting sense, since the fBm B_H is a nonstationary process.

A proper stationary model in lieu of fBm is the fractional Riesz-Bessel motion (fRBm), which is a continuous-time Gaussian process $X(t)$ with spectral density function of the form

$$f(\lambda) = \frac{c}{|\lambda|^{2\alpha}(1+\lambda^2)^{\beta}}, \quad \lambda \in \mathbb{R}, \tag{2}$$

where $0 < c < \infty$, $0 < \alpha < 1$ and $\beta > 0$.
Observe that the process $X(t)$ is stationary if $0 < \alpha < 1/2$ and is nonstationary with stationary increments if $1/2 \le \alpha < 1$, and under the conditions $0 < \alpha < 1/2$, $\beta > 0$ and $\alpha + \beta > 1/2$, the function $f(\lambda)$ in (2) is well-defined for both $|\lambda| \to 0$ and $|\lambda| \to \infty$ due to the presence of the component $(1+\lambda^2)^{-\beta}$, $\beta > 0$, which is the Fourier transform of the Bessel potential. The exponent α determines the long-range dependence, or self-similarity of fRBm, while the exponent β indicates the second-order intermittency of the process. Comparing (1) and (2), we observe that the spectral density of fBm is the limiting case as $\beta \to 0$ that of fRBm with Hurst index $H = \alpha - 1/2$. Thus, the form (2) means that fRBm may exhibit both LRD and second-order intermittency.

Finally, the data can also occur in the form of a realization of a "mixed" short-long-memory stationary process $X(t)$ with spectral density given by $f(\lambda) = f_L(\lambda) f_S(\lambda)$, where $f_L(\lambda)$ and $f_S(\lambda)$ are the long- and short-memory components, respectively.

So, it is important to consider a model that will include the above discussed cases. To specify the model we need the following definition: we say that a nonnegative locally integrable function $f(\lambda)$ satisfies the *Muckenhoupt condition* $(\mathcal{A}_2)$ (or has Muckenhoupt type singularities), if

$$\sup \frac{1}{|J|^2} \int_J f(\lambda)\, d\lambda \int_J \frac{1}{f(\lambda)}\, d\lambda < \infty, \tag{A_2}$$

where the supremum is over all intervals J, and $|J|$ stands for the length of an interval J.

Observe that the spectral densities satisfying Muckenhoupt condition may possess singularities. In particular, functions of the form $f(\lambda) \sim |\lambda|^{\alpha}$ satisfy Muckenhoupt condition if and only if $-1 < \alpha < 1$. Condition (A_2) controls the singularities of the spectral density $\theta(\lambda)$, and describes the dependence structure of the underlying process $X(t)$. It is a regularity condition for $X(t)$, and means that the maximal coefficient of correlation between the "past" and the "future" of the process $X(t)$ is less than 1. We say that a stationary process $X(t)$ is a Muckenhoupt process, if its spectral density function $f(\lambda)$ satisfies Muckenhoupt condition.

4 Descriptions of Problems and Some Results

1. The Parametric Estimation Problem. Assuming that the underlying process $X(u)$ is Gaussian and its spectral density $f(\lambda) = f(\lambda, \theta)$ depends on an unknown p-dimensional parameter $\theta = (\theta_1, \ldots, \theta_p)$, investigate whether various estimators of θ, including the exact maximum likelihood, Whittle and minimum contrast estimators of θ, constructed on the basis of an observation $X = (X(1), \ldots, X(T))$ (in the discrete-time case), and $\{X(u), \quad 0 \le u \le T\}$ (in the continuous-time case), possess "nice" statistical properties (unbiasedness, consistency, asymptotic normality, asymptotic efficiency and local asymptotic minimaxity).

This and related problems such as approximation of the likelihood function, local asymptotic normality of families of Gaussian distributions, were considered in papers [2] - [6] and [8], where for some classes of discrete-time processes were found "good" approximations of the likelihood function, was established the local asymptotic normality property of parametric families of Gaussian distributions, and proved that the Whittle statistics are unbiased, consistent, asymptotically normal and asymptotically efficient estimators for unknown spectral parameters.

2. The Nonparametric Estimation Problem. Suppose we observe a finite realization $\mathbf{X}_T = \{X(1), \ldots, X(T)\}$ of a zero mean real–valued stationary Gaussian process $X(t)$ with an *unknown* spectral density function $f(\lambda)$, $\lambda \in [-\pi, \pi]$. We assume that $f(\lambda)$ belongs to a given class $F \subset L^p[-\pi, \pi]$ $(p > 1)$ of spectral densities possessing some smoothness properties. Let $\Phi(\cdot)$ be some *known* functional, the domain of definition of which contains F. The distribution of the process $X(t)$ is completely determined by the spectral density, and we consider $f(\lambda)$ as an infinite–dimensional "parameter" on which the distribution of $X(t)$ depends.
The problem is to estimate the value $\Phi(f)$ of the functional $\Phi(\cdot)$ at an unknown point $f \in F$ on the basis of an observation $\mathbf{X}_T$, and to investigate the asymptotic (as $T \to \infty$) properties of the suggested estimators. The main objective is construction of asymptotically efficient estimators for $\Phi(f)$.
This and related problems were considered in papers [9] - [11], [16], [18], [19], [25] - [28], where, in particular, the concepts of $H-$ and IK– efficiency of estimators, based on the variants of Hájek–Ibragimov–Khas'minskii convolution theorem and Hájek–Le Cam local asymptotic minimax theorem were defined, and was proved that the *simple "plug-in"* statistic $\Phi(I_T)$, where $I_T = I_T(\lambda)$ is the periodogram of the underlying process $X(t)$ with an unknown spectral density $f(\lambda)$, is H- and IK-asymptotically efficient estimator for a linear functional $\Phi(f)$, while for a nonlinear smooth functional $\Phi(f)$ an H- and IK-asymptotically efficient estimator is the *non-simple "plug-in"* statistic $\Phi(\widehat{f}_T)$, where $\widehat{f}_T$ is a sequence of "undersmoothed" kernel estimators of the unknown spectral density $f(\lambda)$.
The problem for discrete-time stationary stochastic fields were discussed in papers [14] and [24], while the papers [15] and [39] are devoted to the continuous-time case.

3. Testing hypotheses about spectrum of stationary process. Suppose we observe a finite realization $\mathbf{X}_T = \{X(1), \ldots, X(T)\}$ of a centered mean real–valued stationary Gaussian process $X(t)$, $t = 0, \pm 1, ...$ The problem of hypotheses testing is: basing on $\mathbf{X}_T$ construct goodness-of-fit tests for testing a composite hypothesis H_0 that the hypothetical spectral density of the process $X(t)$ has the form $f(\lambda, \theta)$, where $\lambda \in [-\pi, \pi]$ and $\theta = (\theta_1, \ldots, \theta_p)'$ is an unknown vector parameter.
This problem was considered in papers [7] and [29]. In the cases where $f(\lambda, \theta)$ can possess Muckenhoupt–type "weak" zeros and/or "strong" zeros of polynomial type that does not depend on parameter θ, the limiting distribution of the statistics $\Phi'_T(\hat{\theta})\Phi_T(\hat{\theta})$, where $\widehat{\theta}_T$ is the asymptotic estimate of maximum likelihood of θ, and $\Phi_T(\hat{\theta})$ is a suitable chosen measure of divergence of the hypothetical spectral density $f(\lambda, \theta)$ and empirical spectral density $I_T(\lambda)$, was described.
This result is an extension of the well-known Chernov and Lehmann result for independent observations.

4. Limit theorems and the large deviation principle for Toeplitz type stochastic quadratic forms and functionals. Let $X(t)$, $t \in \mathbb{R}$, be a centered real-valued discrete- or continuous-time stationary Gaussian process with spectral density $f(\lambda)$. The problem is: describe the asymptotic distribution of the Toeplitz type quadratic form (or functional, in the continuous-time case) Q_T of process $X(t)$, generated by an integrable even function $g(\lambda)$, depending on the properties of spectral density $f(\lambda)$ and generating function $g(\lambda)$. This problem arise both in parametric and nonparametric estimation of the spectrum of the underlying process $X(t)$. Sufficient (close to necessary) conditions in terms of $f(\lambda)$ and $g(\lambda)$ ensuring central limit theorems for standard normalized quadratic functionals Q_T of continuous-time stationary Gaussian process were obtained in papers [12], [15] and [35]. The problem for discrete-time processes was solved in papers [14], [31] and [33]. The large deviation principle for Toeplitz type random quadratic forms for discrete-time processes was partially discussed in [22].

5. The Prediction Problem. For simplicity we state the problem in the discrete-time case. Let $X(u)$, $u \in \mathbb{Z} = \{0, \pm 1, \ldots\}$, be a second order discrete-time stationary process with spectral density $f(\lambda)$, $\lambda \in [-\pi, \pi]$. Suppose we have observed the past of our process $X(u)$ for a length of time T, that is, the stochastic variables $X(-T), \ldots, X(-1)$, and want to predict the value $X(0)$ of $X(u)$ at $u = 0$. We look for a best mean square linear predictor $\widehat{X}(0)$, that is, $\widehat{X}(0)$ should be a linear combination of the observed values $X(-T), \ldots, X(-1)$, and $\widehat{X}(0)$ should minimize the mean square prediction error $\sigma_T^2(f)$:

$$\sigma_T^2(f) = \min_{\{a_k\}} \mathbb{E} \left| X(0) - \sum_{k=1}^{T} a_k X(-k) \right|^2,$$

where $\mathbb{E}[\cdot]$ stands for expectation. Let $\sigma^2(f)$ be the prediction error based on the entire past of the process $X(u)$. The quantity $\delta_T(f) = \sigma_T^2(f) - \sigma^2(f)$ is the "relative" prediction error of the predictor $\widehat{X}(0)$. It is clear that $\delta_T(f) \geq 0$ and $\delta_T(f) \to 0$ as $T \to \infty$. One of the basic problem in prediction theory of stationary processes is:
Direct Prediction Problem. Describe the rate of decrease of the "relative" prediction error $\delta_T(f) = \sigma_T^2(f) - \sigma^2(f)$ to zero as $T \to \infty$, depending on the dependence structure (short, intermediate or long memory) of the underlying stochastic process $X(t)$ and the smoothness properties of its spectral density $f(\lambda)$. The problem for discrete-time processes was considered in papers [1] and [23], and for continuous-time processes in [30] and [38]. In particular, in [23] was proved that for $\gamma > 0$ the estimates $\delta_T = O(T^{-\gamma})$ and $\delta_T = o(T^{-\gamma})$ as $T \to \infty$ are valid for sufficiently broad classes of spectral densities that can possess Muckenhoupt-type and polynomial zeros.
In [30] and [38] were obtained explicit expressions for prediction error in the cases of first and second order continuous-time stationary mixed autoregressive/moving average (ARMA) processes with spectral densities vanishing at zero.

6. Asymptotic behavior of Toeplitz and Fredholm determinants. The prediction problem is closely related to the analytical problem of description of the asymptotic behavior of Toeplitz (discrete-time processes) and Fredholm (continuous-time processes) determinants. These questions were considered in [1], [23], [30] and [38].

7. Approximations of products of Toeplitz operators and matrices. These approximations and the corresponding error bounds are of importance in the statistical analysis of stationary processes (asymptotic distributions and large deviations of Toeplitz type quadratic functionals, estimation of the spectral parameters and functionals, asymptotic expansions of the estimators, etc.). These questions were considered in [10], [11], [15], [35] - [37], [40], and [41].

5 The Future

1. There are many new interesting results obtained in the field of statistics of stationary processes that are not reflected in the existing monographs, and there is a need to summarize these results in a separate book, and currently, I am working on the monograph "Stationary Gaussian Processes: Estimation and Prediction". On the other hand,

2. Many aspects of the above stated, and related problems are still open, and require further investigation. Some of these questions are the subject of the research project (joint with Professor at Boston University

Murad Taqqu) "Long and Short Memory Stationary Processes: Prediction and Estimation", supported by the National Science Foundation Grant # DMS-0706786 (2007-2010).

The papers [35] – [41] are completed within the above project, and the following works are in progress:

1. The prediction problem for discrete-time stationary Gaussian processes with M.S. Taqqu).
2. Asymptotically Efficient Nonparametric Estimation of Spectral Functionals for Gaussian Stationary Models.
3. Asymptotic Efficiency of the Sample Covariances of Gaussian Stationary Processes.
4. Asymptotic Behavior of the Finite Predictor for Continuous-time Stationary Processes.
5. Trace Classes of Toeplitz Operators and Matrices (with A. A. Sahakyan).
6. Statistics of Stationary Gaussian processes.

3. **Future Research:** The following problems are of great interest.

1. The inverse prediction problem: For a given rate of decrease of the prediction error to zero, describe the process compatible with that rate. Specify then dependence structure and the smoothness properties of their spectral densities.
2. Description of the asymptotic behavior of prediction error for deterministic and generalized stationary processes.
3. Baxter's inequality for continuous-time stationary processes and relationship with partial autocorrelation function and the parameter function for Krein's system.
4. Characterizations of regularity conditions of stationary processes (in particular, Muckenhoupt processes) in terms of covariance and partial autocorrelation functions.
5. Asymptotic efficiency of minimum contrast estimators for continuous-time stationary processes.
6. Obtain necessary and sufficient conditions for applicability of central limit theorems for standard normalized Toeplitz type random quadratic forms and functionals, and establish large deviation principle for continuous-time processes.
7. Applications of the obtained and expected results in finance and economics.

6 Presentations

The above results were presented in a number of International Conferences, Workshops and Seminars. In particular:

- International Congress of Mathematicians, Zurich, Switzerland (1994).
- Vilnius International Conferences on Probability and Statistics (1998, 2002).
- International Conference on Limit Theorems in Probability and Statistics, Hungary (1982).
- 27th International Conference on Stochastic Processes and their Applications, Cambridge, UK (2001).
- International Conferences "Harmonic Analysis and Approximations, Armenia (1998, 2001, 2005).
- International Conferences "Mathematical Problems of Statistical Physics", Armenia (2000, 2002).

- International Conference "Application of Multivariate Statistical Analysis in Economics and Estimation Theory", Armenia (2004).
- Brown University Analysis Seminar, November, 2005.
- Boston University Probability and Statistics Seminars, 2005, 2006, 2008.
- "Barcelona Conference on Asymptotic Statistics (BAS2008)", 2008.
- International Conference "Statistique Asymptotique des Processus Stochastiques VII" LeMans, France, March 2009.
- "The 23rd New England Statistics Symposium", University of Connecticut, April, 2009.
- Yale University Statistics Seminar, November, 2009.

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