A Recipe For The Eigenfunctions of Stationary Gaussian Processes

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Abstract

An extension to the approach of solving for the eigenfunctions of Gaussian integral covariance operators described in *Stochastic finite elements: a spectral approach* is described for the class of wide-sense stationary Gaussian processes. It is applicable non-square-integrable kernels over an unbounded (noncompact) domains if the canonical metric is such that the corresponding metric entropy integral is finite thus rendering the integral covariance operator compact relative to the canonical metric induced by thge process. This essentially provides an effective version of (the ineffective) Aronszajn's theorem for stationary Gaussian procesees.

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1 The Spectral Approach to Stochastic Processes

1.1 The Gelfand-Vilenkin Spectral Representation

The majority of the results on the representation of random processes have been derived for the class of second order processes[4]; one of the most important of which is the `Gelfand-Vilenkin spectral representation` which states in its most general form

$$w\,(x,\theta) = \int g(x)\, d\,\mu(\theta) \tag{1}$$

where $w\,(x,\theta)$ is a stochastic process whose covariance function $C_{ww}(x_1,x_2)$ can be expressed as

$$C_{ww}(x_1,x_2) = \int g(x_1)\; g(x_2)\, d\,\mu_1(\theta)\, d\,\mu_2(\theta) \tag{2}$$

In equation (1), $g(x)$ is a deterministic function and $d\,\mu(\theta)$ is an orthogonal set function, also termed orthogonal stochastic measure, defined on the σ-field Ψ of random events. An important specialization of the spectral expansion occurs if the process $w\,(x,\theta)$ is wide stationary. In this case, equation (1) can be shown to reduce to the Wiener-Khintchine relation [8] and we have

$$w\,(x,\theta) = \int_{-\infty}^{\infty} e^{i\omega^T x}\, d\,\mu(\omega,\theta) \tag{3}$$

and

$$C_{ww}(x_1,x_2) = \int_{-\infty}^{\infty} e^{i(\omega_1 x_1 - \omega_2 x_2)^T}\, S(\omega)\, d\,\omega \tag{4}$$

where the symbol T denotes vector transposition, These spectral representations are significant but limited to deterministic systems under the influence of stochastic processes. This limitation arises because these representations require differentials of random functions, placing them in an infinite-dimensional space, which complicates the development of computational algorithms. Similarly,[7, Ch.1 Bibliogaphical notes, p.18] highlights a challenge in extending von Neumann's zero-sum two-person games to stochastic processes, hindered by the same issue of infinite-dimensionality.

1.2 The Karhunen-Loeve Expansion

The Karhunen-Loeve expansion is an extensively used spectral representation theorem, which expands the random process $w\,(x,\theta)$ in terms of a denumerable set of orthogonal random variables in the form

$$w\,(x,\theta) = \sum_{i=1}^{\infty} \mu_i(\theta)\; g_i(x) \tag{5}$$

where $\{\mu_i(\theta)\}$ is a set of random variable projections and $\{g_i(x)\}$ are the functions of the integral covariance operator associated to the Gaussian process having the covariance kernel of $w(x,\theta)$. Since equation (?) is a quantization of the random process it can be viewed as a representation of the process $w(x,\theta)$ as a curve in the Hilbert space spanned by the set $\{g_i(x)\}$ expressed as a direct sum of orthogonal projections in this Hilbert space whereby the magnitudes of the projections on successive basis vectors are proportional to the corresponding eigenvalues of the covariance function associated with the eigenfunctions of the process $w(x,\theta)$. Collectively, the representations discussed up to [4, 2.2] can be thought of as linear operators or filters acting on processes with independent increments.

1.2.1 Derivation

Theorem 1. *The random process $w(x,\theta)$ can be represented by the Karhunen-Loeve expansion defined by the Fourier-like series as*

$$w(x,\theta) = \sum_{n=0}^{\infty} \sqrt{\lambda_n}\, \xi_n(\theta)\, f_n(x) \tag{6}$$

where $\{\xi_n(\theta)\}$ is a said to be a set of 'random' variables to be determined by projecting the process $w(x,\theta)$ onto the $n-$th eigenfunction and λ_n is the n-th eigenvalue corresponding to the n-th eigenfunction of the corresponding integral covariance operator $\{f_n(x)\}$

Proof. Let $w(x,\theta)$ be a random process, function of the position vector x defined over the domain D, with θ belonging to the space of random events Ω. Let $\bar{w}(x)$ denote the expected value of $w(x,\theta)$ over all possible realizations of the process, and $C(x_1,x_2)$ denote its covariance function. By definition of the covariance function, it is bounded, symmetric and positive definite. Thus, it has the eigenfunction expansion [4, 2.3.1]

$$C(x_1,x_2) = \sum_{n=0}^{\infty} \lambda_n\, f_n(x_1)\, f_n(x_2) \tag{7}$$

where λ_n and $f_n(x)$ are the eigenvalue and the eigenfunction of the covariance kernel. And, specifically, that they are the solution to the integral equation

$$\int_D C(x_1,x_2)\, f_n(x_1)\, d\,x_1 = \lambda_n\, f_n(x_2) \tag{8}$$

Due to the symmetry and the positive definiteness of the covariance kernel, its eigenfunctions are orthogonal and form a complete set. They can be normalized according to the following criterion

$$\int_D f_n(x)\, f_m(x)\, d\,x = \delta_{nm} \tag{9}$$

where δ_{nm} is the Kronecker delta. Clearly, $w(x,\theta)$ can be written as

$$w\,(x,\theta) = \bar{w}(x) + \alpha(x,\theta) \tag{10}$$

where $\alpha(x,\theta)$ is a process with zero mean and covariance function $C(x_1,x_2)$. The process $\alpha(x,\theta)$ can be expanded in terms of the eigenfunctions $f_n(x)$ as

$$\alpha(x,\theta) = \sum_{n=0}^{\infty} \xi_n(\theta)\sqrt{\lambda_n}\, f_n(x) \tag{11}$$

Second order properties of the random variables ξ_n can be determined by multiplying both sides of equation (11) by $\alpha(x_2,\theta)$ and taking the expectation on both sides. Specifically, it is found that

$$\begin{aligned} C(x_1,x_2) &= \langle \alpha(x_1,\theta)\,\alpha(x_2,\theta)\rangle \\ &= \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} \langle \xi_n(\theta)\,\xi_m(\theta)\rangle \sqrt{\lambda_n\,\lambda_m}\, f_n(x_1)\, f_m(x_2) \end{aligned} \tag{12}$$

Then, multiplying both sides of equation (12) by $f_k(x_2)$, integrating over the domain D, and making use of the orthogonality of the eigenfunctions, yields

$$\begin{aligned} \int_D C(x_1,x_2)\, f_k(x_2)\, d\,x_2 &= \lambda_k\, f_k(x_1) \\ &= \sum_{n=0}^{\infty} \langle \xi_n(\theta)\,\xi_k(\theta)\rangle \sqrt{\lambda_n\,\lambda_k}\, f_n(x_1) \end{aligned} \tag{13}$$

Multiplying once more by $f_l(x_1)$ and integrating over D gives

$$\int_D\int_D f_l(x_1)\, f_k(x_1)\, d\,x_1 = \sum_{n=0}^{\infty} E\,\langle \xi_n(\theta)\,\xi_k(\theta)\rangle \sqrt{\lambda_n\,\lambda_k}\,\delta_{nl} \tag{14}$$

Then, using equation (9) leads to

$$\lambda_k\,\delta_{kl} = \sqrt{\lambda_k\,\lambda_l}\,\langle \xi_k(\theta)\,\xi_l(\theta)\rangle \tag{15}$$

Equation (15) can be rearranged to give

$$\langle \xi_k(\theta)\,\xi_l(\theta)\rangle = \delta_{kl} \tag{16}$$

Thus, the random process $w\,(x,\theta)$ can be written as

$$w\,(x,\theta) = \bar{w}(x) + \sum_{n=0}^{\infty} \xi_n(\theta)\sqrt{\lambda_n}\, f_n(x) \tag{17}$$

where

$$\langle \xi_n(\theta) \rangle = 0 \tag{18}$$

$$\langle \xi_n(\theta)\, \xi_m(\theta) \rangle = \delta_{nm} \tag{19}$$

and λ_n, $f_n(x)$ are solution to equation (8). Truncating the series in equation (17) at the M^{th} term, gives

$$w\,(x,\theta) = \bar{w}(x) + \sum_{n=0}^{M} \xi_n(\theta) \sqrt{\lambda_n}\, f_n(x) \tag{20}$$

An explicit expression for $\xi_n(\theta)$ can be obtained by multiplying equation (11) by $f_n(x)$ and integrating over the domain D. That is,

$$\xi_n(\theta) = \frac{\int_D \alpha(x,\theta)\, f_n(x)\, d\,x}{\sqrt{\lambda_n}} \tag{21}$$ □

1.2.2 Reproducing Kernel Hilbert Spaces (RKHS)

The essential thing that the Reproducing Kernel Hilbert Space (RKHS) paradigm provides, is that either of equations (11) or (20), are expressions for the congruence that maps the Hilbert space spanned by the functions $f_n(x)$ to the Hilbert space spanned by the random process, or equivalently, the set of random variables $\{\xi_n(\theta)\}$. It is this congruence along with the covariance function of the process that determines uniquely the random process $w\,(x,\theta)$ as can be seen by observing the similarity of equations (11) and (20) with equations (7) and (8), respectively. If a function can be represented in terms of linear operations on the family $\{C(\,\cdot\,, x_2)\}$, then f belongs to the RKHS corresponding to the kernel $C(x_1, x_2)$, and the congruence between the two Hilbert spaces can be realized by the same linear operations used to represent f in terms of $\{C(\,\cdot\,, x_2)\}$, $x_2 \in D$.

Another point of practical importance is that the expansion given by equation (19) can be used in a numerical simulation scheme to obtain numerical realizations of the random process. It is optimal in the Fourier sense, as it minimizes the mean square error resulting from truncation after a finite number of terms.It is well known from functional analysis that the steeper a bilinear form decays to zero as a function of one of its arguments, the more terms are needed in its spectral representation in order to reach a preset accuracy. Noting that the Fourier transform operator is a spectral representation, it may be concluded that the faster the autocorrelation function tends to zero, the broader is the corresponding spectral density, and the greater the number of requisite terms to represent the underlying random process by the Karhunen-Loeve expansion. Most theorems are limited to bounded-intervals and square-integrable kernels. This setup does not induce the ergodic assumption for the process since the domain is bounded; however, for many purposes the ergodic condition is not necessary but it may restored by extending the limits of integration in equation (35) to infinity.[4, 2.3.2][1, 5.6]

1.3 Properties

1.3.1 Error Minimization

Lemma 2. ***Error Minimization****: The generalized coordinate system defined by the eigenfunctions of the covariance kernel is optimal in the sense that the mean-square error resulting from a finite representation of the process $w(x,\theta)$ is minimized.*

Proof. Given a complete orthonormal set of functions $h_n(x)$, the process $w(x,\theta)$ can be approximated in a convergent series of the form

$$w(x,\theta) = \sum_{n=0}^{\infty} \lambda_n \xi_n(\theta)\, h_n(x) \tag{22}$$

Truncating equation (21) at the M^{th} term results in an error ϵ_M equal to

$$\epsilon_M = \sum_{n=M+1}^{\infty} \lambda_n \xi_n(\theta)\, h_n(x) \tag{23}$$

Multiplying equation (21) by $h_m(x)$ and integrating throughout gives

$$\xi_m(\theta) = \frac{\int_D w(x,\theta)\, h_m(x)\, dx}{\sqrt{\lambda_m}} \tag{24}$$

where use is made of the orthogonality property of the set $h_n(x)$. Substituting equation (23) for $\xi_m(\theta)$ back into equation (22), the mean-square error ϵ_M^2 can be written as

$$\epsilon_M^2 = \left[\sum_{m=M+1}^{\infty} \sum_{n=M+1}^{\infty} \int_D \int_D \langle \xi_m(\theta)\, \xi_n(\theta) \rangle\, h_m(x_1)\, h_n(x_2)\, dx_1\, dx_2 \right]^2 \tag{25}$$

Integrating equation (24) over D and using the orthonormality of the set $\{h_i(x)\}$ yields

$$\int_D \epsilon_M^2\, dx = \sum_{m=M+1}^{\infty} \int_D \int_D R_{ww}(x_1,x_2)\, h_m(x_1)\, h_m(x_2)\, dx_1\, dx_2 \tag{26}$$

The problem, then, is to minimize $\int_D \epsilon_M^2$ subject to the orthonormality of the functions $h_n(x)$. In other words, the solution minimizes the functional given by the equation

$$\mathcal{F}[h(x)] = \sum_{m=M+1}^{\infty} \int_D \int_D R_{ww}(x_1,x_2)\, h_m(x_1)\, h_m(x_2)\, dx_1\, dx_2 - \lambda_m \left[\int_D h_m(x)\, h_m(x)\, dx - 1 \right] \tag{27}$$

Differentiating equation (26) with respect to $h_i(x)$ and setting the result equal to zero, gives

$$\frac{\partial \mathcal{F}[h(x)]}{\partial h_i(x)} = \int_D \int_D R_{ww}(x_1, x_2)\, h_i(x_1)\, d\, x_1 - \lambda_i\, h_i(x_2)\, d\, x_2 = 0 \tag{28}$$

which is satisfied when

$$\int_D R_{ww}(x_1, x_2)\, h_i(x_2)\, d\, x_2 = \lambda_i\, h_i(x_1) \tag{29}$$ □

1.3.2 Uniqueness of the Expansion

Lemma 3. ***Uniqueness****: The random variables appearing in an expansion of the kind given by equation (10) are orthonormal if and only if the orthonormal functions $\{f_n(x)\}$ and the constants $\{\lambda_n\}$ are respectively the eigenfunctions and the eigenvalues of the covariance kernel as given by equation (8).*

Proof. The "if" part is an immediate consequence of equation (11). To show the "only if" part, equation (12) can be used with

$$\langle \xi_n(\theta)\, \xi_m(\theta) \rangle = \delta_{nm} \tag{30}$$

to obtain

$$C(x_1, x_2) = \sum_{n=0}^{\infty} \lambda_n\, f_n(x_1)\, f_n(x_2) \tag{31}$$

Multiplying both sides by $f_m(x_2)$ and integrating over D gives

$$\int_D C(x_1, x_2)\, f_m(x_2)\, d\, x_2 = \sum_{n=0}^{\infty} \lambda_n\, f_n(x_1)\, \delta_{nm} = \lambda_m\, f_m(x_1) \tag{32}$$ □

1.3.3 Expansion of Gaussian Processes

Let $w\,(x, \theta)$ be a Gaussian process with covariance function $C(x_1, x_2)$. Then $w\,(x, \theta)$ has the Karhunen-Loeve decomposition given by equation (17) with the random variables $\xi_i(\theta)$ forming a Gaussian vector. That is, any subset of $\{\xi_i(\theta)\}$ is jointly Gaussian. Since these random variables are uncorrelated, their Gaussian property implies their independence. Some important consequences derive from this property. Specifically,

$$\langle \xi_1(\theta), \ldots, \xi_{2n+1}(\theta) \rangle = 0 \tag{33}$$

and

$$\langle \xi_1(\theta), \ldots, \xi_{2n}(\theta) \rangle = \sum \prod \langle \xi_i(\theta)\, \xi_j(\theta) \rangle \tag{34}$$

where the summation extends over all the partitions of the set $\{\xi_i(\theta)\}_{i=1}^{2n}$ into sets of two elements, and the product is over all such sets in a given partition. Furthermore, it can be shown (Loeve, 1977) that for Gaussian processes, the Karhunen-Loeve expansion is almost surely convergent.

1.3.4 Minimum Representation Entropy

The minimum representation of entropy property is worth mentioning even though it only references and no details were given in [4].

1.4 Solution of the Integral Equation

The usefulness of the Karhunen-Loeve expansion hinges on the ability to solve the integral equation of the form

$$\int_D C(x_1, x_2)\, f(x_2)\, d\, x_2 = \lambda\, f(x_1) \tag{35}$$

where $C(x_1, x_2)$ is an autocovariance function. Equation (35) is a homogeneous Fredholm integral equation of the second kind. Being an autocovariance function, by definition the kernel $C(x_1, x_2)$ is bounded, symmetric, and positive definite. This fact simplifies the ensuing analysis considerably by virtue of the fact that positive definite kernels implies the existence of an RKHS for the kernel and its spectral density given by its Fourier transform is non-negative and non-decreasing over its domain of definition by Aronszajn's Theorem and Bochner's theorem respectively.

1.5 Exact Solutions For Stationary Processes

At the time of writing of [4] there was no general method for the solution of the integral equation (35) corresponding to irrational spectra and furthermore most of the results are for finite bounded intervals [4, 2.3.2] and thus do not presume ergodicity which may however be restored by extending the limits of integration in equation (35) to infinity [4, 2.3.2] Here, we present an apparently novel an rather elegant way way to deduce the eigenfunctions of any stationary process, kernel square-integrable or not, domain unbounded or not.

In [4, 2.3.2] a Galerkin type procedure is described for the solution of the Fredholm equation (35) where $h_i(x)$ is any complete set but here it will be shown that the best choice is not just any complete set of functions in the Hilbert space H but the specific complete orthogonal set given by orthogonal complement of the the Fourier transforms of the orthogonal polynomials whose orthogonality measure is equal to the spectral density of the process.

Definition 4. *Let the term 'spectral basis set' denote the orthogonal polynomials whose orthogonality measure is equal to the spectral density of the process which is given by the Fourier transform of the covariance kernel function.*

For example, suppose that the kernel is given by a stationary (translation-invariant) process where the covariance is a function of one variable given by the difference between two points only

$$C(t,s) = J_0(t-s) \tag{36}$$

Each eigenfunction of the kernel $C(t-s)$ may then be represented exactly as

$$f_k(x) = h_k(x) \tag{37}$$

by defining $h_i(x)$ to be the orthogonal complement of the normalized Fourier transforms $Y_n(y)$ which are given by normalizing

$$\hat{T}_n(y) = \int_{-1}^{1} T_n(x)\, e^{ixy}\, \mathrm{d}x \tag{38}$$

.

the finite Fourier transform of the spectral basis set T_n(here the Chebyshev type-I polynomials[?] which is just the usual infinite Fourier transform with the integration restricted to the range $-1 \ldots 1$ since $T_n(x) = 0 \forall x \notin [-1,1]$ or equivalently taking the functions value to be 0 outside the range -1 to 1). Taking the Fourier transform of the elements of the spectral basis set takes it back into the time/space domain from the spectral(frequency) domain and by orthogonalizing the with respect to the unweighted L^2 inner product the optimal basis for the representation of the covariance function itself is constructed by noting that the partial sums of $h_i(x)$ will then pointwisely converge to $K = J_0$

of the orthogonal polynomials spanning the spectral basis set T_n given by the Gram-Schidt recursions

$$h_i(y) = \hat{T}_n^{\perp}(y) = \hat{T}_n(y) - \sum_{m=1}^{n-1} \frac{\langle \hat{T}_n(y), \hat{T}_m^{\perp}(y) \rangle}{\langle \hat{T}_m^{\perp}(y), \hat{T}_n^{\perp}(y) \rangle} \hat{T}_n^{\perp}(y) \tag{39}$$

which in the case when $K = J_0$ the spectral density is seen to be equal to

$$S(\omega) = \int_0^{\infty} J_0(x)\, e^{ix\omega}\, \mathrm{d}x = \begin{cases} \dfrac{1}{\sqrt{1-\omega^2}} & \omega \in (-1,1) \\ 0 & \text{otherwise} \end{cases} \tag{40}$$

so that we identify the spectral density with the Chebyshev polynomials of the first kind T_n, since their orthogonality measure is, in fact, equal to the spectral density in the case $K(t,s) = J_0(t-s)$. Recalling that the Chebyshev polynomials' orthogonality relation is

$$\int_{-1}^{1} T_n(\omega)\, T_m(\omega)\, S(\omega)\, \mathrm{d}\omega = \begin{cases} 0 & n \neq m \\ \pi & n = m = 0 \\ \dfrac{\pi}{2} & n = m \neq 0 \end{cases} \tag{41}$$

This error is equal to the difference between the left hand side and the right hand side of equation (35). Substituting equation (37) into equation (35) yields the following expression for the error

$$e_N = \sum_{i=0}^{N} d_i^{(k)} \left[\int_D \int_D C(x_1, x_2)\, h_i(x_2)\, d\, x_2 - \lambda_n\, h_i(x_1) \right] \tag{42}$$

Requiring the error to be orthogonal to the approximating space yields equations of the following form $\forall j = 1, \ldots, N$

$$(e_N, h_j(x)) = 0 \tag{43}$$

Equivalently,

$$\sum_{i=1}^{N} d_i^{(k)} \left[\int_D \int_D C(x_1, x_2)\, h_i(x_2)\, d\, x_2\, h_j(x_1)\, d\, x_1 \right] - \lambda_n \int_D h_i(x)\, h_j(x)\, d\, x = 0 \tag{44}$$

Denoting

$$C_{ij} = \int_D \int_D C(x_1, x_2)\, h_i(x_2)\, h_j(x_1)\, d\, x_1\, d\, x_2 \tag{45}$$

$$B_{ij} = \int_D h_i(x)\, h_j(x)\ d\, x \tag{46}$$

$$D_{ij} = d_i^{(j)} \tag{47}$$

$$\Lambda_{ij} = \delta_{ij}\, \lambda_j \tag{48}$$

equation (44) becomes

$$C\, D = \Lambda B\, D \tag{49}$$

where C, B and D are three N-dimensional matrices whose elements are given by equations (45)-(46). Equation (49) represents a generalized algebraic eigenvalue problem which may be solved for the matrix D and the eigenvalues λ_k. Backsubstituting into equation (37) yields the eigenfunctions of the covariance kernel. The preceding procedure can be implemented using piecewise polynomials as the basis for the expansion. With this choice of basis functions, the columns of the matrix $\mathbf{D}$ become the eigenvectors computed at the respective nodal points of the induced mesh, and the $i\, j^{th}$ element of the matrix $\mathbf{C}$ becomes the weighted correlation between the process at nodes i and j. Note that both matrices $\mathbf{C}$ and $\mathbf{B}$ are symmetric positive definite, a fact that substantially simplifies the numerical solution. The Galerkin scheme described above can be shown to be equivalent to a variational treatment of the problem. This property ensures that the computed eigenvalues are a lower bound of the correspondingly numbered exact eigenvalues. This implies that the convergence of each eigenvalue is monotonic in N. Further, note that the accuracy in estimating the eigenvalues is better than that achieved for the eigenfunctions (Delves and Mohamed, 1985).

1.5.1 $\int_0^\infty J_0(t-s)\,f(t)\mathrm{d}t$

Lemma 5. *The functions*

$$\begin{aligned}\psi_n(y) &= (-1)^n \sqrt{\frac{4\,n+1}{y}}\, J_{2n+\frac{1}{2}}(y) \\ &= (-1)^n \sqrt{\frac{4n+1}{\pi}}\, j_{2n}(y)\end{aligned} \tag{50}$$

are orthonormal over the interval 0 *to* ∞*, i.e.,*

$$\int_0^\infty \psi_n(y)\,\psi_m(y)\;d\,y = \delta_{nm},$$

where δ_{nm} *is the Kronecker delta.*

Proof. Consider the integral

$$I = \int_0^\infty \psi_n(y)\,\psi_m(y)\;d\,y \tag{51}$$

Substituting $\psi_n(y)$ and $\psi_m(y)$, we get:

$$I = \int_0^\infty \sqrt{\frac{4\,n+1}{y}}\,(-1)^n\,J_{2n+\frac{1}{2}}(y) \sqrt{\frac{4\,m+1}{y}}\,(-1)^m\,J_{2m+\frac{1}{2}}(y)\;d\,y \tag{52}$$

This simplifies to:

$$I = \sqrt{(4\,n+1)\,(4\,m+1)}\,(-1)^{n+m} \int_0^\infty \frac{J_{2n+\frac{1}{2}}(y)\,J_{2m+\frac{1}{2}}(y)}{y}\;d\,y \tag{53}$$

Using the orthogonality relation for Bessel functions with $\nu = -\frac{1}{2}$:

$$\int_0^\infty \frac{J_{\nu+2n+1}(t)\,J_{\nu+2m+1}(t)}{t}\;d\,t = \frac{\delta_{nm}}{2\,(2\,n+\nu+1)} \tag{54}$$

for $\nu = -\frac{1}{2}$, we have:

$$\int_0^\infty \frac{J_{2n+\frac{1}{2}}(t)\, J_{2m+\frac{1}{2}}(t)}{t}\, dt = \frac{\delta_{nm}}{4n+1} \tag{55}$$

Substituting this result back into the integral, we have:

$$I = \sqrt{(4n+1)(4m+1)}\,(-1)^{n+m} \frac{\delta_{nm}}{4n+1} \tag{56}$$

For $n \neq m$, $\delta_{nm} = 0$, yielding $I = 0$. For $n = m$, $\delta_{nm} = 1$, giving:

$$I = \frac{\sqrt{(4n+1)^2}}{4n+1} = \frac{4n+1}{4n+1} = 1 \tag{57}$$

Hence, $\psi_n(y)$ and $\psi_m(y)$ are orthonormal. □

Theorem 6. *The eigenvalues of*

$$\int_0^\infty J_0(x-y) * \psi_n(x)\, dx = \lambda_n\, \psi_n(y) \tag{58}$$

are given by

$$\begin{aligned} \lambda_n &= \int_0^\infty J_0(x)\, \psi_n(x)\, dx \\ &= \int_0^\infty J_0(x) \sqrt{\frac{4n+1}{y}}\,(-1)^n\, J_{2n+\frac{1}{2}}(y)\, dx \\ &= \sqrt{\frac{4n+1}{\pi}} \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma(n+1)^2} \end{aligned} \tag{59}$$

where $\psi_n(x)$ is the orthonormal set defined in Lemma 1.

Proof. To show that $\psi_n(y)$ are eigenfunctions of the integral operator with kernel $J_0(x-y)$ and to find the corresponding eigenvalues, we start with the given equation:

$$\int_0^\infty J_0(x-y)\, \psi_n(x)\, dx = \lambda_n\, \psi_n(y)$$

where

$$\psi_n(y) = \sqrt{\frac{4n+1}{y}}\,(-1)^n\, J_{2n+\frac{1}{2}}(y)$$

and the eigenvalues are:

$$\lambda_n = \int_0^\infty J_0(x)\, \psi_n(x)\, dx = \sqrt{\frac{4n+1}{\pi}}\, \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma(n+1)^2}$$

To find λ_n, we compute:

$$\lambda_n = \int_0^\infty J_0(x)\, \psi_n(x)\, dx$$

Substituting $\psi_n(x)$:

$$\lambda_n = \int_0^\infty J_0(x) \sqrt{\frac{4n+1}{x}}\, (-1)^n\, J_{2n+\frac{1}{2}}(x)\, dx$$

Using the integral of products of Bessel functions:

$$\int_0^\infty x^{-\frac{1}{2}}\, J_0(x)\, J_{2n+\frac{1}{2}}(x)\, dx = \sqrt{\frac{4n+1}{\pi}}\, \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma(n+1)^2}$$

Thus:

$$\lambda_n = \sqrt{\frac{4n+1}{\pi}}\, \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma(n+1)^2}$$

This completes the proof that $\psi_n(y)$ are eigenfunctions of the integral operator with kernel $J_0(x-y)$ and the corresponding eigenvalues are as given. □

Definition 7. *Let $j_n(x)$ is the spherical Bessel function of the first kind,*

$$\begin{aligned} j_n(z) &= \sqrt{\frac{\pi}{2z}}\, J_{n+\frac{1}{2}}(x) \\ &= \frac{\sin(z)\, R_{n,\frac{1}{2}}(z) - \cos(z)\, R_{n-1,\frac{3}{2}}(z)}{\sqrt{z}} \end{aligned} \tag{60}$$

where $R_{n,v}(z)$ are the so-called Lommel polynomials [5]

$$R_{n,v}(z) = \frac{\Gamma(n+v)}{\Gamma(v)} \left(\frac{2}{z}\right)^n {}_2F_3\left(\left[-\frac{n}{2}, \frac{1}{2} - \frac{n}{2}\right]; [v, -n, 1-v-n]; -z^2\right) \tag{61}$$

where ${}_2F_3$ is a generalized hypergeometric function which are really rational functions which are said to be "polynomial in $\frac{1}{z}$".

Conjecture 8. *The series*

$$\begin{aligned} J_0(t) &= \sum_{k=0}^{\infty} \lambda_k \psi_k(t) \\ &= \sum_{k=0}^{\infty} \sqrt{\frac{4\,n+1}{\pi}} \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma\left(n+1\right)^2} (-1)^n \sqrt{\frac{4\,n+1}{\pi}}\, j_{2n}(t) \\ &= \sum_{k=0}^{\infty} \frac{4\,n+1}{\pi} \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma\left(n+1\right)^2} (-1)^n\, j_{2n}(t) \end{aligned} \tag{62}$$

converges uniformly for all complex t *except the origin where it has a regular singular point where* $\lim_{t\to 0} J_0(t) = 1$.

Conjecture 9. *The eigenfunctions of the stationary integral covariance operator*

$$[T\psi_n](x) = \int_0^{\infty} J_0\left(x-y\right) \psi_n(x) \mathrm{d}x = \lambda_n \psi_n(x) \tag{63}$$

are given by

$$\psi_n(y) = (-1)^n \sqrt{\frac{4\,n+1}{\pi}}\, j_{2n}(y) \tag{64}$$

and the eigenvalues are given by

$$\begin{aligned} \lambda_n &= \int_{-\infty}^{\infty} J_0(x)\, \psi_n(x)\, \mathrm{d}x \\ &= \sqrt{\frac{4\,n+1}{\pi}} \frac{\Gamma\left(n+\frac{1}{2}\right)^2}{\Gamma\left(n+1\right)^2} \\ &= \sqrt{\frac{4\,n+1}{\pi}}\, (n+1)^2_{-\frac{1}{2}} \end{aligned} \tag{65}$$

where $(n+1)^2_{-\frac{1}{2}}$ *is the Pochhammer symbol(ascending/rising factorial).*

Definition 10. *The spectral density of a stationary process is the Fourier tranform of the covariance kernel due to Wiener-Khinchine theorem.*

Definition 11. *Let* $S_n(x)$ *be the orthogonal polynomials whose orthogonality measure is equal to the spectral density of the process. These polynomials shall be called the spectral polynomials corresponding to the process.*

Example 12. Let the kernel function be given by $K(t,s) = J_0(t-s)$ then identify the orthogonal polynomial sequence associated with the spectral density

$$S(\omega) = \int_{-\infty}^{\infty} J_0(x)\, e^{ix\omega}\, \mathrm{d}x = \begin{cases} \dfrac{2}{\sqrt{1-\omega^2}} & \omega \in (-1,1) \\ 0 & \text{otherwise} \end{cases} \tag{66}$$

as being twice the orthogonality measure of the Type-I Chebyshev polynomials $T_n(x)$ so that the orthogonal polynomial sequence is identified as

$$S_n(x) = \sqrt{2} T_n(x) \tag{67}$$

so that

$$\int_{-1}^{1} S_n(\omega)\, S_m(\omega)\, S(\omega)\, \mathrm{d}\omega = \begin{cases} 0 & n \neq m \\ 2\pi & n = m = 0 \\ \pi & n = m \neq 0 \end{cases} \tag{68}$$

Remark 13. If the spectral density does not equal the orthogonality measure of a known set of orthogonal polynomials then such a set can always be generated by applying the Gram-Schmidt process to the monomials so that they are transformed into a set that is orthogonal with respect any given spectral density (of a stationary process).

Definition 14. *The sequence $\hat{S}_n(y)$ of Fourier transforms of the spectral polynomials $S_n(x)$ is given by*

$$\hat{S}_n(y) = \int_{-1}^{1} S_n(x) e^{ixy} \mathrm{d}x \tag{69}$$

Example 15. The Fourier transforms of the Chebyshev polynomials are just the usual infinite Fourier transforms with the integration restricted to the range $-1 \ldots 1$ since $T_n(x) = 0 \forall x \notin [-1,1]$). Equivalently, the spectral density function can be extended to take the value 0 outside the interval $[-1,1]$. The derivation of

$$\begin{aligned} \hat{T}_n(y) &= \int_{-\infty}^{\infty} e^{-ixy} T_n(x) d\, y = \int_{-1}^{1} e^{-ixy} T_n(x) d\, x \\ &= \int_{-\infty}^{\infty} e^{-ixy}\, {}_2F_1\left(\begin{matrix} n, & -n \\ & \frac{1}{2} \end{matrix} \middle| \frac{1}{2} - \frac{x}{2} \right) d\, x \\ &= \frac{i}{y} \left(e^{-iy} F_n^+(y) - e^{i(\pi n + y)} F_n^-(y) \right) \end{aligned} \tag{70}$$

where

$$F_n^{\pm}(y) = {}_3F_1\left(\begin{matrix} 1, & n, & -n \\ & & \frac{1}{2} \end{matrix} \middle| \frac{\pm iy}{2} \right) \tag{71}$$

can be found in [2].

Definition 16. *Let $Y_n(y)$ be the normalized spectral polynomials $S_n(x)$*

Example 17. When $K = J_0$ the spectral polynomials are given by

$$S_n(x) = \sqrt{2} T_n(x) \tag{72}$$

so that

$$\begin{aligned} Y_n(y) &= \frac{\hat{T}_n(y)}{|\hat{T}_n|} \\ &= \frac{i}{y} \left(\frac{e^{-iy} F_n^+(y) - e^{i(\pi n + y)} F_n^-(y)}{\sqrt{\frac{4(-1)^n \pi - (2n^2 - 1)}{4n^2 - 1}}} \right) \end{aligned} \tag{73}$$

where the L^2 norm of $\hat{T}_n(y)$ is given by

$$\begin{aligned} |\hat{T}_n| &= \sqrt{\int_{-\infty}^{\infty} \hat{T}_n(y)^2 \mathrm{d}y} \\ &= \sqrt{\frac{4(-1)^n \pi - (2n^2 - 1)}{4n^2 - 1}} \end{aligned} \tag{74}$$

Conjecture 18. *The eigenfunctions of the integral covariance operator (63) are given by the orthogonal complement of the normalized Fourier transforms $Y_n(y)$ of the spectral polynomials (via the Gram-Schmidt process)*

$$\psi_n(y) = Y_n^{\perp}(y) = Y_n(y) - \sum_{m=1}^{n-1} \frac{\langle Y_n(y), Y_m^{\perp}(y) \rangle}{\langle Y_m^{\perp}(y), Y_m^{\perp}(y) \rangle} Y_m^{\perp}(y) \tag{75}$$

can be equivalently expressed as

$$\begin{aligned} \psi_n(y) &= (-1)^n \sqrt{\frac{4\,n+1}{\pi}}\, j_{2n}(y) \\ &= (-1)^n \sqrt{\frac{4\,n+1}{\pi}} \sqrt{\frac{\pi}{2\,y}}\, J_{2n+\frac{1}{2}}(y) \\ &= (-1)^n \sqrt{\frac{4\,n+1}{2\,y}}\, J_{2n+\frac{1}{2}}(y) \\ &= \sqrt{\frac{4\,n+1}{4\,\pi}} \int_{-1}^{1} P_{2n}(x)\, e^{ixy}\, \mathrm{d}x \end{aligned} \tag{76}$$

Remark 19. Since T is compact due to its self-adjointness and convergence of the eigenvalues to 0 it converges uniformly since compactness implies uniform convergence of the eigenfunctions. TODO: cite/theorems from [6, 3. Reproducing Kernel Hilbert Space of a Gaussian Process]

1.5.2 Simplifying The Convolution

Apply the addition theorem

$$J_0(x-y) = \sum_{k=-\infty}^{\infty} J_k(x)\, J_k(y)$$

to the integral covariance operator

$$\begin{aligned}
[T\psi_n](x) &= \int_0^\infty J_0(x-y)\,\psi_n(y)\,dy \\
&= \int_0^\infty \sum_{k=-\infty}^{\infty} J_k(x)\, J_k(y)\,\psi_n(y)\,dy \\
&= \sum_{k=-\infty}^{\infty} J_k(x) \int_0^\infty J_k(y)\,\psi_n(y)\,dy \\
&= \sum_{k=-\infty}^{\infty} J_k(x) \int_0^\infty J_k(y)\,(-1)^n \sqrt{\frac{4n+1}{\pi}}\, j_{2n}(y)\,dy
\end{aligned}$$

Where $\psi_n(y)$ is:

$$\psi_n(y) = (-1)^n \sqrt{\frac{4n+1}{\pi}}\, j_{2n}(y) = (-1)^n \sqrt{\frac{4n+1}{\pi}} \sqrt{\frac{\pi}{2y}}\, J_{2n+\frac{1}{2}}(y)$$

Substituting

$$\begin{aligned}
\int_0^\infty J_k(y)\,\psi_n(y)\,dy &= \int_0^\infty J_k(y)\,(-1)^n \sqrt{\frac{4n+1}{\pi}}\, j_{2n}(y)\,dy \\
&= \frac{\sqrt{4n+1}\,(-1)^n \sqrt{\pi}\,\Gamma\left(\frac{k}{2}+n+\frac{1}{2}\right)}{2\,\Gamma\left(-n+\frac{k}{2}+\frac{1}{2}\right)\Gamma\left(\frac{k}{2}+n+1\right)\Gamma\left(n+1-\frac{k}{2}\right)}
\end{aligned}$$

Now, putting it all back into the expansion for $[T\psi_n](x)$:

$$[T\psi_n](x) = \sum_{k=-\infty}^{\infty} J_k(x) \frac{\sqrt{4n+1}\,(-1)^n \sqrt{\pi}\,\Gamma\left(\frac{k}{2}+n+\frac{1}{2}\right)}{2\,\Gamma\left(-n+\frac{k}{2}+\frac{1}{2}\right)\Gamma\left(\frac{k}{2}+n+1\right)\Gamma\left(n+1-\frac{k}{2}\right)}$$

Conjecture 20.

$$\sum_{k=0}^{\infty} \psi_k(x)^2 = \frac{1}{\pi} \tag{77}$$

2 Appendix

2.1 A Theorem On The Development of Symmetric Nuclei

Theorem 21. *[3, 11.70] Let $\phi_n(\alpha)$ be a complete set of orthogonal functions satisfying the homogeneous integral equation with symmetric nucleus*

$$\phi(\alpha) = \lambda \int_a^b K(\alpha, \xi)\, \phi(\xi)\, d\xi \tag{78}$$

the corresponding characteristic numbers being $\lambda_1, \lambda_2, \lambda_3, \ldots$ Now suppose that the series $\sum_{n=1}^{\infty} \frac{\phi_n(\alpha)\, \phi_n(\gamma)}{\lambda_n}$ is uniformly convergent when $0 \leqslant a \leq \alpha \leq b \leqslant \infty$, $0 \leqslant a \leq \gamma \leq b \leqslant \infty$. Then it will be shown that

$$K(\alpha, \gamma) = \sum_{n=1}^{\infty} \frac{\phi_n(\alpha)\, \phi_n(\gamma)}{\lambda_n} \tag{79}$$

Proof. For consider the symmetric nucleus

$$H(\alpha, \gamma) = K(\alpha, \gamma) - \sum_{n=1}^{\infty} \frac{\phi_n(\alpha)\, \phi_n(\gamma)}{\lambda_n} \tag{80}$$

If this nucleus is not identically zero, it will possess at least one characteristic number μ. Let $\psi(\gamma)$ be any solution of the equation

$$\psi(\alpha) = \mu \int_a^b H(\alpha, \xi)\, \psi(\xi)\, d\xi \tag{81}$$

which does not vanish identically. Multiply by $\phi_m(\alpha)$ and integrate term-by-term (which we may do since the series converges uniformly by hypothesis proved by other means), and get

$$\int_a^b \psi(\alpha)\, \phi_m(\alpha)\, d\alpha = \mu \int_a^b \int_a^b \left[K(\alpha, \xi) - \sum_{n=1}^{\infty} \frac{\phi_n(\alpha)\, \phi_n(\xi)}{\lambda_n} \right] \psi(\xi)\, \phi_m(\alpha)\, d\xi\, d\alpha = 0 \tag{82}$$

Therefore $\psi(\alpha)$ is orthogonal to $\phi_1(\alpha), \phi_2(\alpha), \ldots$; and so taking the equation

$$\psi(\alpha) = \mu \int_a^b \left[K(\alpha, \xi) - \sum_{n=1}^{\infty} \frac{\phi_n(\alpha)\, \phi_n(\xi)}{\lambda_n} \right] \psi(\xi)\, d\xi \tag{83}$$

we have

$$\psi(\alpha) = \mu \int_a^b K(\alpha, \xi)\, \psi(\xi)\, d\xi \tag{84}$$

Therefore μ is a characteristic number of $K(\alpha, \gamma)$, and so $\psi(\alpha)$ must be a linear combination of the functions $\phi_n(\alpha)$ corresponding to this number; let

$$\psi(\alpha) = \sum_m a_m\, \phi_m(\alpha) \tag{85}$$

Multiply by $\phi_m(\gamma)$ and integrate; then since $\psi(\alpha)$ is orthogonal to all the functions $\phi_m(\alpha)$, we see that $a_m = 0$, so, contrary to hypothesis, $\psi(\alpha) = 0$. The contradiction implies that the nucleus $H(\alpha, \gamma)$ must be identically zero; that is to say, $K(\alpha, \gamma)$ can be expanded in the given series, if it is uniformly convergent. □

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