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<p>→ Research was conducted and directed in the area of stochastic processes by three of the Principal Investigators, S. Cambanis, G. Kallianpur and M.R. Leadbetter, and their associates, and in statistical inference by R.J. Carroll. A summary of the main areas of research activity follows for each Principal Investigator and co-workers. More detailed descriptions of the work of all participants is given in the main body of the report. <i>Keywords: statistical inference, signal processing, white noise, regular least squares, nonparametric estimation.</i></p>			
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## SUMMARY OF RESEARCH ACTIVITY

Research was conducted and directed in the area of stochastic processes by three of the Principal Investigators, S. Cambanis, G. Kallianpur and M.R. Leadbetter, and their associates, and in statistical inference by R.J. Carroll. A summary of the main areas of research activity follows for each Principal Investigator and co-workers. More detailed descriptions of the work of all participants is given in the main body of the report.

### S. Cambanis

Non-Gaussian Signal Processing: Contrasts and similarities between Gaussian and other stable and infinitely divisible signals; two classes of self-similar stable processes with stationary increments; discrimination of stable processes; some new models of stable noise for signal detection; skewed stable signals; regression and random filters; can the bootstrap of the mean work under infinite variance?; the oscillation of infinitely divisible processes; ergodic properties of stationary infinitely divisible processes; multiple integrals of Poisson and Lévy processes.

Digital Processing of Analog Signals: Sampling designs for estimating the integral of stochastic processes; trapezoidal Monte-Carlo integration.

Non-stationary Harmonizable Signals: Prediction of multivariate harmonizable processes; harmonizability and  $V$ - and  $(2,p)$ -boundedness of stochastic processes; stochastic processes as Fourier integrals and dilation of vector measures.

### G. Kallianpur

Nonlinear Filtering and Prediction: Statistical applications of white noise theory; smoothness properties of the conditional expectation in finitely additive white noise filtering.

Stochastic Evolution: Infinite dimensional diffusions in duals of nuclear spaces; stochastic differential equations driven by Poisson process; stochastic evolution equations and weak convergence of their solutions; a Langevin equation for a particle system in stable medium; critical fluctuations in interacting particle systems; macroscopic nonequilibrium dynamics of the exclusion process in a random medium.

Continuation of the study of the stochastic behavior of spatially extended neurons and assemblies of neurons. Fluctuation theorems for large systems of interacting diffusions.

Stochastic analysis on canonical Hilbert space: Feynman integrals and homogeneous chaos expansions. Stratonovich version of Skorokhod integral.

Infinite dimensional parameters: Estimation and robust inference.

#### M.R. Leadbetter

Extremal theory for moderately behaved stationary sequences: Limits of exceedance point processes; exceedance point processes for regular sample functions; high level exceedances in stationary sequences with extremal index; extreme value theory for dependent sequences via the Stein-Chen method of successive approximation; approximations in extreme value theory.

Random measures and extremes for continuous parameter stationary processes: The exceedance random measure for stationary processes; the excursion random measure.

Inference in extreme value theory: A Brownian bridge connected with extreme values; extremal behavior of solutions to a stochastic difference equation with applications to arch-processes.

Exchangeability: exchangeable random measures in the plane.

Subexponential distributions: estimation of convolution tails.

Stationary distributions of Markov chains: their computation through perturbations. Light traffic approximation in queues.

R.J. Carroll

Weighted least squares with weights estimated by replication; Optimal rates of convergence for deconvolving a density; The effect of estimating the mean and variance function in regression; Second order effects in semiparametric heteroscedastic models; Extended quasilielihood; Nonparametric estimation of optimal performance criteria in quality engineering; Minimum detectable concentration in assays; Multiple use calibration; Generalized linear measurement error models; Nearest neighbor regression. Stopping rules in sequential analysis: significance levels and ordered families of distributions.

**RESEARCH IN STOCHASTIC PROCESSES**

**STAMATIS CAMBANIS**

The work briefly described here was developed in connection with problems arising from and related to the statistical communication theory and the analysis of stochastic signals and systems, and falls into two categories as follows. Item 9 is the result of continuing joint work with E. Masry of the University of California, San Diego. Items 1, 6 and 7 are in collaboration with various visitors to our Center for Stochastic Processes: Lawniczak, Maejima, Nolan and Rosinski. Item 2 is the completed Ph.D. dissertation of M. Marques. Item 8 describes the Ph.D. dissertation of K. Benhenni in its final stage of completion. Finally Items 4 and 5 describe parts of the Ph.D. dissertation research of W. Wu.

I. NONGAUSSIAN SIGNAL PROCESSING: Contrasts and similarities between Gaussian and other stable and infinitely divisible signals.

Are commonly used Gaussian models and signal processing techniques robust to departures from normality? Or are there situations where even small departures from normality may require quite different signal processing techniques? In continuing the exploration of the robustness (or the lack of it) of the Gaussian model within the class of stable and other infinitely divisible models, we have studied the self-similarity, the discrimination, and the signal detection problem for stable signals; the working of the bootstrap of the mean in a heavy tail case; and certain path and ergodic properties of infinitely divisible processes.

1. Two classes of self-similar stable processes with stationary increments [1].

Two disjoint classes of self-similar symmetric stable processes with stationary increments are introduced and studied. The first class consists of linear fractional stable processes, which are related to moving average stable processes, and the second class consists of harmonizable fractional stable processes, which are connected to harmonizable stationary stable processes. The domain of attraction of the harmonizable fractional stable processes is also studied.

2. Discrimination of stable processes [2].

An upper bound for the set of admissible translates of a general  $p^{\text{th}}$  order process is presented, which is a partial analog of the reproducing kernel Hilbert space of a second order process. For invertible processes a dichotomy is established: each translate is either admissible or singular, and the admissible translates are characterized. As a consequence, most continuous time moving averages and all harmonizable processes with nonatomic spectral measure have no admissible translate. Necessary and sufficient conditions for equivalence and singularity of certain product measures are given and applied to the problem of distinguishing a sequence of random vectors from affine transformations of itself; in particular sequences of stable random variables are considered and the singularity of sequences with different indexes of stability is proved. Sufficient conditions for singularity and necessary conditions for absolute continuity are given for  $p^{\text{th}}$  order processes. Finally certain stable processes, such as independently scattered measures and harmonizable processes, are shown to have the dichotomy property, i.e., they are either equivalent or singular.

### 3. Some new models of stable noise for signal detection [3].

In most real life signal detection problems the signal is an admissible translate of the noise. We survey some recent results on the admissible translates of stable processes and we contrast them with the analogs for Gaussian processes. Whereas Gaussian moving averages and Fourier transforms of independent increments processes have rich classes of admissible translates, their stable counterparts frequently have all translates singular. By removing the requirement of independence of the increments, we introduce stable processes that are generalized moving averages and harmonizable which can have rich classes of admissible translates and therefore can serve as stable noise models in signal detection. These are generally nonstationary processes but we also show a class of stationary generalized moving averages.

### 4. Can the bootstrap of the mean work under infinite variance? [4]

For independent and identically distributed random variables with infinite variance belonging in the domain of attraction of a symmetric stable law, it is known that the sample mean appropriately normalized converges to a stable law. Athreya [5] showed that a certain normalized bootstrap version of the sample mean has a limiting random distribution, implying that the naive bootstrap could fail in a heavy tail case. We show that the limiting random distribution of Athreya's bootstrap is not stable even on the average and we study its averaged asymptotic law. We construct an appropriately normalized bootstrap version of the sample mean and we show that on the average it has a limiting stable distribution. A way is thus suggested for the bootstrap of the mean to work in this heavy tail case.

5. Skewed stable signals: Regression and random filters which preserve input stability [6].

The general case of possibly asymmetric stable processes is studied. Necessary and sufficient conditions for the linearity of regression are developed when absolute moments exist, (i.e. the index of stability exceeds one. When the index of stability is less than one and first absolute moments are infinite, necessary and sufficient conditions are given for first conditional absolute moments to exist, and the linearity of regression is studied. Also the random filters which preserve the stability of all stationary asymmetric stable inputs are characterized as the filters with random time shift.

6. The oscillation of infinitely divisible processes [7].

A sufficient condition is given for infinitely divisible processes with no Gaussian component to have nonrandom oscillation. This immediately gives information about the sample paths of such processes, such as a Belyayev type dichotomy for stationary or self-similar processes: their paths are either continuous or everywhere unbounded. The sufficient condition for nonrandom oscillation is shown to be necessary for a large class of infinitely divisible processes to have finite nonrandom oscillation. It is also used to relate path continuity to continuity at each point. Similar results are described for path differentiability.

7. Ergodic properties of stationary infinitely divisible processes [8].

We derive spectral necessary and sufficient conditions for stationary symmetric infinitely divisible processes to be ergodic and mixing. We have shown that most (and we still hope to show that all) infinitely divisible processes with a harmonic spectral representation are not ergodic. Therefore they are distinct from the infinitely divisible moving averages, which are

always mixing. This is in sharp contrast with the Gaussian case where all moving averages have a harmonic spectral representation.

## II. DIGITAL PROCESSING OF ANALOG SIGNALS

Continuous time signals are typically observed at discrete times and inferences are drawn on the basis of these samples. The performance of the sampling designs and estimators has been studied for the problem of estimating the integral of a time series using certain deterministic and random sampling designs.

### 7. Sampling designs for estimating the integral of stochastic processes [9].

In certain problems involving time series, it is of interest to find the best sampling designs in the allocation of the observations over an interval and to form simple and efficient estimators. Specifically, the problem of estimating the weighted integral of a stochastic process from observations at a finite number of sampling points is considered. Sacks and Ylvisaker (1966-70) found a sequence of asymptotically optimal sampling designs using optimal coefficient estimators for processes with exactly 0 or 1 quadratic mean derivatives. These results are extended to processes with exactly  $k$  quadratic mean derivatives for every  $k=0,1,\dots$ . These estimators require precise knowledge of the process covariance and are not robust. Simple nonparametric estimators based on an adjusted trapezoidal rule using similar sampling designs are introduced whose performance is asymptotically optimal for processes with exactly  $k$  quadratic mean derivatives for every  $k = 0,1,2,\dots$ .

### 9. Trapezoidal Monte Carlo integration [10].

The approximation of weighted integrals of random processes by the

trapezoidal rule based on an ordered random sample is considered. For processes which are once mean-square continuously differentiable and for weight functions which are twice continuously differentiable, it is shown that the rate of convergence of the mean-square integral approximation error is precisely  $n^{-4}$ , and the asymptotic constant is also determined. No faster rate of convergence can be generally achieved.

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## G. KALLIANPUR

Research carried out during the year is described under the following broad categories:

1. Nonlinear filtering.
2. Infinite dimensional (nuclear space valued) diffusions.
3. Discontinuous stochastic differential equations in duals of nuclear spaces.
4. Fluctuation theorems for large systems of interacting diffusions.
5. Stochastic analysis on canonical Hilbert space.

1. Nonlinear filtering and prediction theory [1].

A book on the subject by Kallianpur and Karandikar has just been published [1]. It is an expanded and improved version of the white noise theory developed over the last five years in collaboration with R.L. Karandikar. Two new features (the results of new research) which have either not been reported, or not adequately described in previous reports are the following:

(i) (with H.P. Huccke and R.L. Karandikar) [2]. It is shown that for a wide class of signal processes and bounded  $g$ , the conditional expectation  $\Pi(g,y)$  in the white noise filtering model is a  $C^\infty$ -functional of the observations in the sense that  $\pi(g,y)$  and its Frechét derivatives (which exist) are random variables (called "accessible") on the quasicylindrical probability space on which the observation model is defined. This solves the problem posed to Kallianpur by Professor P. Malliavin some years ago.

(ii) Statistical applications of the white noise theory are briefly discussed in [1, Chapter XI]. These include parameter estimation in linear models, likelihood ratio and signal detection and the filtering problem for countable state Markov processes.

## 2. Infinite dimensional diffusions (with I. Mitoma and R. Wolpert) [3].

Diffusions taking values in infinite dimensional spaces occur in such diverse fields as nonlinear filtering, infinite particle systems and population genetics. More specifically this work has been motivated by the study of the motion of random strings and the development of more realistic models for the description of the voltage potential of a spatially extended neuron.

The specific stochastic differential equation (SDE) studied is of the form

$$dX_t = A(t, X_t)dt + B(t, X_t)dW_t$$

where  $W=(W_t)$  is a  $\phi'$ -valued Wiener process and  $\phi'$  is the strong dual of a countably Hilbertian nuclear space  $\phi$ . The coefficient functions  $A: \mathbb{R}_+ \times \phi' \rightarrow \phi'$  and  $B: \mathbb{R}_+ \times \phi' \rightarrow \mathcal{L}(\phi', \phi')$  satisfy certain measurability, continuity, coercivity and growth conditions. Using a stochastic Galerkin method, the existence of a solution to the martingale problem and of a weak solution is established. This is a major difference between the present work and other works known to us on infinite dimensional (Banach or Hilbert space valued) SDE's (such as the work of Krylov and Rozovskii). The monotonicity condition is used only to prove uniqueness, using a Yamada-Watanabe type argument.

## 3. Discontinuous stochastic differential equations in duals of nuclear spaces

(with G. Hardy and S. Ramasubramanian) [4].

The class of SDE's investigated includes as a special case a stochastic model for the voltage potential of a spatially extended neuron that incorporates the nonlinear phenomenon of reversal potentials. The SDE in integral form is given by

$$X(t) = X_0 + \int_0^t A(s, X(s))ds + \int_0^t \int_U G(s, X(s-), u) \tilde{N}(dsdu),$$

where  $\tilde{N}$  is compensated Poisson random measure. The idea of the proof is similar

to that of (2), based on first establishing a solution to the martingale problem, using the idea of the stochastic Galerkin method. Uniqueness is proved under the additional assumption of monotonicity. What is crucial to both problems (2) and (3) are suitable dimension-independent bounds to certain moments of the solution to a finite-dimensional approximation to the SDE.

Research under Items (2) and (3) was begun earlier and was described in the previous Annual Report. The completion of the proof of the main result in (2) required surmounting certain difficulties which have now been solved. The work under (3) has also been completed.

Further work suggested by (2) and (3), which it is proposed to study in the coming year, is concerned with nonlinear stochastic evolutions driven by general (possibly discontinuous) nuclear space valued martingales. The theory of canonical decompositions of such semimartingales is expected to play an important role in this problem.

4. Fluctuation theorems for large systems of interacting (infinite dimensional) diffusions (with I. Mitoma) [5].

Large assemblies of neurons interact in complicated ways. One such model of interactions is studied yielding a central limit theorem for such large systems. It is shown that the weak solution of a Langevin-type stochastic differential equation exists uniquely on a space of generalized functionals which is an appropriate model for the central limit theorem for an interacting system of spatially extended neurons.

The Langevin-type SDE in question is of the form

$$dX(t) = L^*(t)X(t)dt + dW(t)$$

where  $L$  is formally a second order differential operator. A generalized solution of the above SDE is a stochastic process which is a continuous linear

functional on a class  $\mathfrak{F}_\phi$  of smooth functionals on  $\phi'$  (dual of a nuclear space  $\phi$ ). For each  $F \in \mathfrak{F}_\phi$ ,  $W_F(t)$  is a continuous, additive Gaussian process. The notion of a generalized solution is defined and its existence is proved under suitable conditions.

The work is related to some recent work of J.D. Deuschel [6]. The research opens up a class of new problems dealing with fluctuation theorems for different kinds of interactions in particle systems as well as neuronal systems.

##### 5. Stochastic analysis on canonical Hilbert space (with G.W. Johnson) [7].

This work is an outgrowth of an investigation of P.A. Meyer's ideas on a distribution-theoretic approach to the Feynman integral. Two of the questions raised in the paper of Y.Z. Hu and P.A. Meyer [11] are the following:

(a) Let  $F(x)$  be a square integrable Wiener functional defined for  $x \in \Omega_1$  where  $\Omega_1$  is the support of the standard Wiener measure. What are the natural ways of defining  $F_\sigma(y)$  for  $y \in \Omega_\sigma$ , the support of the Wiener measure with variance parameter  $\sigma^2$  ( $\sigma \neq 1$ ) such that  $F_\sigma$  is the "same random variable" on  $\Omega_\sigma$  that  $F$  is on  $\Omega_1$ ?

(b) Given a multiple Wiener-Itô "integral" defined on the Cameron-Martin space  $\Omega_0$  of the form

$$I_p^0(m) = \int \cdots \int f_p(t_1, \dots, t_p) m(t_1) \cdots m(t_p) dt_1 \cdots dt_p.$$

$f_p \in \text{sym } L^2(\mathbb{R}_+^p)$  and  $m \in L^2(\mathbb{R}_+)$ , how does one obtain a "natural" extension to  $\Omega_\sigma$  for all  $\sigma > 0$  (including  $\sigma = 1$ )?

Problem (a) has been studied and some of the formulas indicated without proof in [11] have been rigorously derived. These results are being written up for publication. The ramifications to the theory of Feynman integrals are being explored further.

In the monograph of Kallianpur and Karandikar referred to under (1), a

theory of "accessible" random variables taking values in  $\mathbb{R}^n$  or in a general Polish space has been developed and applied to non linear prediction and filtering. It is interesting that this theory can be applied to solve Problem (b). It is shown that if  $\psi_p(m) := I_p^0(m)$  belongs to  $\mathcal{F}(H^{\otimes p})$  i.e. its kernel  $f_p$  has the property that certain traces  $\text{Tr}^k f_p$  ( $2k \leq p$ ) exist and belong to  $\text{sym } L^2(\mathbb{R}_+^{p-2k})$ , then the lifting  $R\psi_p$  exists (with standard Wiener space as the representation space) and  $R\psi_p$  satisfies the Hu-Meyer formula given in [11] given in terms of multiple Wiener-Itô integrals. An inverse formula expressing the multiple integral  $I_p(f_p)$  in terms of liftings of symmetric multilinear forms is also obtained.

An exciting prospect opened up by this work is the possibility of developing a "Malliavin" calculus on  $(H, \mathcal{G}, \mu)$  where  $\mu$  is finitely additive, canonical Gauss measure on  $H$ . Some preliminary results, parallel to those of Nualart and Zakai [8] are obtained, among them, the definition of an operator of derivation  $D$  and  $\Lambda$  which acts on  $\psi_p$  in the same way that the Malliavin operator acts on  $I_p(f_p)$ . Finally, Skorokhod liftings are defined leading to the definitions of a Stratonovich version of the Skorokhod integral.

A special feature is that symmetric, continuous  $p$ -linear forms are the natural building blocks of this theory just as multiple Wiener-Itô integrals are the basic elements in the Nualart-Zakai exposition of Malliavin calculus [8]. A great deal remains to be done.

## 6. Stochastic evolution equations (SEE's) (with V. Perez-Abreu) [9,10].

(i) The work on SEE's described in the previous Annual Report has now been published [9].

(ii) The weak convergence of solutions of SEE's in duals of nuclear spaces has been studied with a view to applications to fluctuation theorems in infinite particle systems and systems of neurons. The SEE's considered are of the form

$$dX_t = A_n'(t)X_t dt + dM_t^n, \quad X_0 = \eta^n \quad (n=1,2,\dots)$$

where  $M^n$  is an  $L^2$ -martingale and  $A_n(t)$  is the generator of a  $(C_0,1)$  semigroup on a Frechét nuclear space. Under suitable conditions it is shown that the solution  $X^n$  converges weakly to the solution  $X$  of a similar see when  $M^n$  converges to  $M$  and  $A_n(t)$  converges to  $A(t)$  in a certain sense. The results will appear in 1988 or 1989 [10].

Ph.D. students of G. Kallianpur

1. R. Selukar: On estimation of Hilbert space valued parameters [12].

A key result of Ibragimov and Hazminski has been generalized to hold for estimating functions (not necessarily the likelihood) and for infinite dimensional parameters. The method of sieves is then applied together with this result to obtain consistent estimators for the drift function of a linear stochastic differential equation. Among the other problems considered are (a) the estimation of a drift parameter in the observation process in a linear filtering model and (b) the estimation of the intensity function of a Poisson process. For the latter problem a result on the rate of convergence is derived, depending on smoothness assumptions on the true intensity.

2. D. Baldwin: Robust inference for infinite dimensional parameters [13].

The work is concerned with another aspect of the estimation of infinite dimensional parameters - those occurring in infinite dimensional stochastic differential equations. The motivation comes from applications to neurophysiology, especially, the problem of estimating the voltage potential of a spatially extended neuron.

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13. D. Baldwin, Robust inference for infinite dimensional parameters, Ph.D. Dissertation, in progress.

### M. ROSS LEADBETTER

During this reporting period M.R. Leadbetter conducted research in two main areas: (1) Extremal theory for "moderately behaved" stationary sequences, and (2) Random measures and extremal theory for continuous parameter stationary processes. The work done and results obtained for each area are detailed below, the main emphasis being on (2). Other activities are described under (3).

#### 1. Extremal theory for moderately behaved stationary sequences.

The focus of extreme value theory for dependent sequences in recent years, has been to obtain results which apply under the most general conditions possible. For example the paper [1] (publishing previous results under this contract) considers a stationary sequence satisfying essentially only a very mild long range dependence restriction. No restriction is placed in that work on local dependence, which can be quite high and lead to clustering of large values of the sequence. Further the clusters can in general have a very complicated structure - consisting mainly of high values but potentially interspersed with quite low values within the one cluster.

In most practical situations of interest, however, a cluster would normally be envisaged as consisting of consecutive high values. Hence an investigation was undertaken to obtain conditions on a stationary sequence under which the general clusters would have the simple "coherent" structure. In this work (with a student, S. Nandagopalan) the structure of clusters was investigated and a condition obtained under which they must necessarily consist of "uninterrupted high values". This condition is milder than the usual "D'" condition (cf. [2]) which eliminates clustering altogether. The new condition still allows clustering, but guarantees that clusters are of the simpler coherent form. It thus does not describe the most general behavior possible, but rather delineates

a wide class of cases of the most practical importance.

A further section of this work concerned the asymptotic equivalence of three point processes associated with high values, viz. (a) exceedances of high levels, (b) upcrossings of high levels, and (c) positions of clusters of high values. Part of this research has been reported in [3] and is summarized as follows:

It is known that any point process limits for the (time normalized) exceedances of high levels by a stationary sequence is necessarily Compound Poisson, under general dependence restrictions. This results from the clustering of exceedances where the underlying Poisson points represent cluster positions, and the multiplicities correspond to cluster sizes. Here we investigate a class of stationary sequences satisfying a mild local dependence condition restricting the extent of local "rapid oscillation". For this class, criteria are given for the existence and value of the so-called "extremal index" which plays a key role in determining the intensity of cluster positions. Cluster size distributions are investigated for this class and in particular shown to be asymptotically equivalent to those for length of "excursions" (i.e. runs of consecutive exceedances) above the level.

Further results in this area will be reported as work proceeds.

## 2. Random measures and extremes for continuous parameter stationary processes.

As described in the previous annual report, a theory for exceedance random measures has been developed under the contract paralleling that for exceedances in discrete time (reported in [1]). In this the exceedance random measure is defined as the amount of time in arbitrarily specified time sets for which the continuous parameter process exceeds a given level (with suitable normalizations). Compound Poisson limit theorems were obtained for this random measure as the time interval and levels increase. Analogously to the discrete time case, such results allow computation of the (marginal) asymptotic distributions of the largest (or second largest, third largest, etc.) local maxima of the process. The most recent results obtained for this case have been reported in [4], whose summary follows:

Two common approaches to extremal theory for stationary processes involve (a) consideration of point processes of upcrossings of high levels and (b) use of the total exceedance time above such levels. The approach (a) yields a greater variety of interesting results regarding the "global" and local maxima, but requires more by way of regularity conditions on the sample paths, than does the approach (b).

In this work both approaches are combined by consideration of the "exceedance random measure" thereby obtaining general results under weak conditions on the sample functions. These include previously known results in the case where more sample function regularity is assumed.

Asymptotic joint distributions of the local maxima are not obtainable from these results. However as in discrete time such distributions may be obtained by consideration of exceedances for multiple levels. Alternatively they may be obtained from limits for a random measure in the plane which we have referred to as the *excursion random measure*, and which summarizes the joint behavior of all possible exceedance random measures for arbitrary levels.

In this research (which is joint with T. Hsing) the possible distributional limits for the excursion random measure have been characterized and "constructive theorems" obtained, giving sufficient conditions for such limits. It is planned that this work will be reported in [5].

Application of the results obtained has been made to stationary normal processes. It is found that the limiting random measure in the plane has a certain non-random component which can be explicitly described. This non-randomness arises by virtue of the fact that high peaks of such processes are known to have approximately parabolic form and which can in fact be simply described by just one random parameter. Investigations have begun into a class of such processes and some general properties have been obtained. Work is

continuing on this topic and results will be reported in due course.

As noted in the previous report, use of the exceedance random measure measure is particularly natural and significant in the case of higher dimensional index sets - i.e. for random fields. A parallel theory for random fields is being developed - undertaken primarily by S. Nandagopalan and will be reported when complete. In particular these results include extensions of many of the classical extremal theorems, to the random field context.

Finally, work has begun on obtaining more general results for continuous parameter processes by "marking" exceedances by the entire excursion above a high level rather than just the time above the level. This work is in its preliminary stages but promises to yield further understanding of extremal properties in continuous time situations. In particular results for particular marks (such as areas above high levels) are also expected to be obtainable.

### 3. Other activities

The Special Invited Paper on extremal theory solicited by the Annals of Probability was completed and published ([6]). The article solicited by the ISI Review on the life and work of Harold Cramér was also completed and has been published ([7]).

### References

1. T. Hsing, J. Hüslér and M.R. Leadbetter, Limits for exceedance point processes, University of North Carolina Center for Stochastic Processes Technical Report No. 150, Sept. 86, Probability Theory and Related Fields, 78, 1988, 97-112.
2. M.R. Leadbetter, G. Lindgren and H. Rootzén, Extremes and related properties of random sequences and processes, Springer Statistics Series, 1983.
3. M.R. Leadbetter and S. Nandagopalan, On exceedance point processes for "regular" sample functions. University of North Carolina Center for Stochastic Processes Technical Report No. 230, Apr. 88. To appear in Proceedings Volume, Oberwolfach Conf. on Extremal Value Theory, Ed. J. Hüslér and R. Reiss, Springer.
4. M.R. Leadbetter, The exceedance random measure for stationary processes.

University of North Carolina Center for Stochastic Processes Technical Report No. 215, Nov. 87.

5. T. Hsing and M.R. Leadbetter, The excursion random measure, University of North Carolina Center for Stochastic Processes Technical Report, in preparation.
6. M.R. Leadbetter and H. Rootzén, Extremal theory for stochastic processes, Special Invited Paper, Ann. Probability, 16, 1988, 431-478.
7. M.R. Leadbetter, H. Cramér 1895-1985, ISI Review, 56, 1988, 89-97.

**M. TERESA ALPUIM**

During her three month visit Dr. Alpuim studied the asymptotic behavior of extreme order statistics from stationary sequences with high local dependence. Joint limiting laws were obtained by determining the asymptotic joint distributions for the numbers of exceedances of multiple levels. The work was reported in [1] whose abstract follows:

This paper considers stationary sequences with extremal index  $\theta$ ,  $0 < \theta \leq 1$ , and satisfying an extension of Leadbetter's D condition. For these sequences we prove that the limit law of high level exceedances is of the Compound Poisson Type and specify the parameters. The joint limit law of exceedances of multiple levels is also given, and consequently that of any  $r$  upper order statistics.

**Reference**

1. M. T. Alpuim, High level exceedances in stationary sequences with extremal index, University of North Carolina Center for Stochastic Processes Technical Report No. 217, Dec. 1987. Stochastic Proc. Appl., to appear.

Professor Bather assisted with the organization of a fall semester seminar devoted to certain stochastic processes in sequential analysis, and presented several talks. In addition, he completed the following two reports concerned with foundational issues for stopping rules arising in sequential analysis.

1. Stopping rules and observed significance levels [1].

It is well known how to combine the significance levels observed in a number of independent experiments. When this number is a random variable determined by a stopping rule, the observed significance level can still be calculated if there is an acceptable ordering of the points in the extended sample space. But what can be said if the stopping time is ill-defined? This paper obtains explicit lower bounds on the level of significance by considering orderings based on a family of alternative hypotheses. These bounds give some measure of the effect of failing to specify the stopping rule in advance.

2. Stopping rules and ordered families of distribution [2].

There are good reasons for using sequential methods in some statistical decision problems, but a stopping rule that is helpful for deciding whether  $\theta > 0$  or  $\theta < 0$  may not be so good for estimating  $\theta$ . This paper considers the construction of confidence bounds on a real parameter and investigates the relation between the ordering of boundary points that are accessible under the stopping rule and the natural ordering of the parameter space.

#### References

1. J. Bather, Stopping rules and observed significance levels, University of North Carolina Center for Stochastic Processes Technical Report No. 209, Sept. 1987. *Sequential Anal.*, to appear
2. J. Bather, Stopping rules and ordered families of distributions, University of North Carolina Center for Stochastic Processes Technical Report No. 219, Dec. 1987. *Sequential Anal.*, 7, 1988, 111-126

## DONALD DAWSON and LUIS G. GOROSTIZA

The work of Professors Dawson and Gorostiza is concerned with obtaining a Langevin equation for the fluctuation limit of a system of particles migrating according to a symmetric stable process and undergoing critical branching in a random medium [1].

The main problem here is a technical one. The stochastic evolution equation is formally given by  $dY_t = A^* Y_t dt + dZ_t$  on the nuclear triple  $\mathcal{Y}(\mathbb{R}^d) \subset L^2(\mathbb{R}^d) \subset \mathcal{Y}'(\mathbb{R}^d)$ . Here  $A = -(-\Delta)^{\alpha/2}$ ,  $0 < \alpha < 2$ . Unlike the case of the Brownian motion (where  $\Delta$  maps  $\mathcal{Y}(\mathbb{R}^d)$  into itself), in the present problem,  $\phi \in \mathcal{Y}(\mathbb{R}^d)$  does not imply that  $\Delta_\alpha \phi$  and  $S_t \phi$  are in  $\mathcal{Y}(\mathbb{R}^d)$  since they do not decay fast enough at infinity. However, a generalized solution to the above equation is defined and its uniqueness established.

## Reference

1. D.A. Dawson and L.G. Gorostiza, Generalized solutions of a class of nuclear space valued stochastic evolution equations, University of North Carolina Center for Stochastic Processes Technical Report No. 225, Feb. 1988.

## LAURENS DE HAAN

Professor de Haan spent two months as a visitor to the Center in the summer 1988, working on problems of inference in extreme value theory. In particular he considered estimation of parameters of the limiting extreme value distribution, regarding those as parametrized in a single family, rather than the three conventional families. This work is summarized as follows:

1. A Brownian bridge connected with extreme values [1].

A stochastic process formed from the intermediate order statistic is shown to converge to a Brownian bridge under conditions that strengthen the domain of attraction conditions for extreme-value distributions.

Joint work by Dr. de Haan, with Resnick, Rootzén and de Vries concerned the extremal properties of so-called "arch-processes" and is summarized as follows:

2. Extremal behavior of solutions to a stochastic difference equation with applications to arch-processes [2].

Limit distributions of extremes of a process  $\{Y_n\}$  satisfying the stochastic difference equation

$$Y_n = A_n Y_{n-1} + B_n, \quad n \geq 1, \quad Y_0 \geq 0,$$

are considered in this paper, where  $\{A_n, B_n\}$  are i.i.d.  $\mathbb{R}_+^2$ -valued random pairs. A special case of interest is when  $\{Y_n\}$  is derived from a first order ARCH-process. Parameters of the limit law are exhibited: some are hard to calculate explicitly but easy to simulate.

## References

1. L. de Haan, A Brownian bridge connected with extreme values, University of North Carolina Center for Stochastic Processes Technical Report No. 241, Sept. 88.
2. L. de Haan, S.I. Resnick, H. Rootzén, C. de Vries. Extremal behavior of solutions to a stochastic difference equation with applications to arch-processes, University of North Carolina Center for Stochastic Processes Technical Report No. 223, Feb. 1988.

## GABOR HARDY

Dr. Hardy worked on stochastic differential equations on duals of nuclear spaces and completed his Ph.D. Dissertation [1] under G. Kallianpur's supervision.

In the first part [2] the class of stochastic equations investigated includes as a special case a stochastic model for the voltage potential of a spatially extended neuron that incorporates the nonlinear phenomenon of reversal potentials, and is of the form

$$X(t) = X_0 + \int_0^t A(s, X(s)) ds + \int_0^t \int_U G(s, X(s-), u) \tilde{N}(ds du),$$

where  $\tilde{N}$  is compensated Poisson random measure. The existence of a solution is shown by first establishing a solution to the martingale problem, using the idea of the stochastic Galerkin method. Uniqueness is proved under the additional assumption of monotonicity. Crucial in the development are suitable dimension-independent bounds to certain moments of the solution to a finite-dimensional approximation to the stochastic equation.

The second part of his thesis investigates a stochastic equation of the form

$$X(t) = X_0 + \int_0^t b(s, X(s), \mathcal{L}(X)) ds + \int_0^t \sigma(s, X(s), \mathcal{L}(X)) dW(s),$$

where  $W$  is  $d$ -dimensional Brownian motion and  $\mathcal{L}(X)$  denotes the law of the process  $X$ . This is a generalization of McKean's equation.

## References

1. G. Hardy, Stochastic differential equations in duals of nuclear spaces, Ph.D. thesis, University of Minnesota, Institute for Mathematics and Its Applications, Nov. 1987.
2. G. Hardy, G. Kallianpur and S. Ramasubramanian, A nuclear space-valued stochastic differential equation driven by Poisson random measures,

University of North Carolina Center for Stochastic Processes Technical  
Report No. 232, Apr. 88.

## CHRISTIAN HOUDRÉ

Dr. Houdré studied non-stationary models for random signals. Using spectral methods, he introduced and characterized the  $(2,p)$ -bounded classes of stochastic processes. These classes contain both the state space and the stationary processes and, therefore, form a link between spectral and time domain approaches to non-stationarity. This naturally lead to a study of the linear prediction problem for those processes, where he developed a filter which reduces to the Wiener filter for stationary processes and to the Kalman filter in the case of state space representation. He completed the following reports.

1. A vector bimeasure integral with some applications [1].

A Fubini type theorem is obtained for a class of vector bimeasure integrals. Using this bimeasure integral, a characterization is provided of the time domain of a harmonizable process.

2. Harmonizability,  $V$ -boundedness and  $(2,p)$ -boundedness of stochastic processes [2].

Some new classes of discrete time non-stationary processes, related to the harmonizable and  $V$ -bounded classes, are introduced. A few characterizations are obtained which, in turn, unify the  $V$ -bounded theory. Our main results depend on a special form of Grothendieck's inequality.

3. On the prediction theory of multivariate  $(2,p)$ -bounded processes [3].

We study some classical linear prediction and filtering problems for non-stationary processes having a Fourier integral representation. We develop time domain as well as spectral domain properties for these processes, including a Wold decomposition and a decomposition for bimeasures. We also obtain an

autoregressive representation for the optimum predictor and show how this framework unifies both the Wiener and the Kalman theories. Finally, we present an algorithmic study of the linear estimation problem for these processes.

#### 4. Stochastic processes as Fourier integrals and dilation of vector measures

[4].

When representing a stochastic process as a Fourier integral of a random measure, common assumptions used are the norm continuity of the process, the strong  $\sigma$ -additivity of the random measure, and in the stationary case the orthogonality of the vector measure. Here we relax these conditions. We trade off continuity for measurability and obtain a representation theorem for the corresponding processes. We then prove a Grothendieck type inequality which implies that any process represented by such a Fourier integral can be dilated to one whose representing measure has orthogonal increments.

#### References

- [1] C. Houdré, A vector bimeasure integral with some applications, University of North Carolina Center for Stochastic Processes Technical Report No. 214, June 88.
- [2] C. Houdré, Harmonizability,  $V$ -boundedness, and  $(2,p)$ -boundedness of stochastic processes, University of North Carolina Center for Stochastic Processes Technical Report No. 239, Aug. 1988.
- [3] C. Houdré, On the prediction theory of multivariate  $(2,p)$ -bounded processes, University of North Carolina Center for Stochastic Processes Technical Report No. 245, Sept. 1988.
- [4] C. Houdré, Stochastic processes as Fourier integrals and dilation of vector measures, University of North Carolina Center for Stochastic Processes Technical Report No. 246, Sept. 1988.

**JEFFREY J. HUNTER**

In a two month visit in the Spring of 1988, Dr. Hunter studied means for computing stationary distributions of Markov chains, based especially on perturbation methods. The work, reported in [1], is summarized as follows:

An algorithmic procedure is presented for the determination of the stationary distribution of a finite,  $m$ -state, irreducible Markov chain, that does not require the use of methods for solving systems of linear equations. The technique is based upon a succession of  $m$ , rank one, perturbations of the trivial doubly stochastic matrix whose known steady state vector is updated at each stage to yield the required stationary probability vector.

**Reference**

1. J.J. Hunter, The computation of stationary distributions of Markov chains through perturbations, University of North Carolina Center for Stochastic Processes Technical Report No. 227, March 1988.

## GERALD W. JOHNSON

Professor Johnson worked with G. Kallianpur on Feynman integrals and homogeneous chaos expansions [1]. This work is an outgrowth of an investigation of P.A. Meyer's ideas on a distribution-theoretic approach to the Feynman integral.

An exciting prospect opened up by this work is the possibility of developing a "Malliavin" calculus for a finitely additive, canonical Gauss measure on a Hilbert space. Some preliminary results are obtained, among them, the definition of an operator of derivation which acts in a way similar to that of the Malliavin operator. Also Skorokhod liftings are defined leading to the definitions of a Stratonovich version of the Skorokhod integral.

A special feature is that symmetric, continuous p-linear forms are the natural building blocks of this theory just as multiple Wiener-Itô integrals are the basic elements in the Nualart-Zakai exposition of Malliavin calculus.

A more detailed description is given in item number 5 under Kallianpur's heading.

## Reference

1. G. Kallianpur and G.W. Johnson, Stochastic analysis on canonical Hilbert space, University of North Carolina Center for Stochastic Processes Technical Report, in progress.

## OLAV KALLENBERG

Professor Kallenberg spent the summer period as a visitor to the Center, and continued his research in diverse areas of probability theory. During this period he made a major contribution in exchangeability theory reported in [1] and described below.

1. Exchangeable random measures in the plane.

A random measure  $\xi$  on  $[0,1]^2$ ,  $[0,1] \times \mathbb{R}_+$  or  $\mathbb{R}_+^2$  is said to be separately exchangeable, if its distribution is invariant under arbitrary Lebesgue measure preserving transformations in the two coordinates, and jointly exchangeable if  $\xi$  is defined on  $[0,1]^2$  or  $\mathbb{R}_+^2$ , and its distribution is invariant under mappings by a common measure preserving transformation in both directions. In each case, we derive a general representation of  $\xi$  in terms of independent Poisson processes and i.i.d. random variables.

During the current year, Professor Kallenberg also completed work conducted during a previous visit on multiple stochastic integrals. This resulted in a significant and widely acclaimed paper which appeared first as a technical report [2], a summary of which follows.

2. Multiple integration with respect to Poisson and Lévy processes.

Necessary and sufficient conditions are given for the existence of a multiple stochastic integral of the form  $\int \cdots \int f dX_1 \cdots dX_d$ , where  $X_1, \dots, X_d$  are components of a positive or symmetric pure jump type Lévy process in  $\mathbb{R}^d$ . Conditions are also given for a sequence of integrals of this type to converge in probability to zero or infinity, or to be tight. All arguments proceed via reduction to the special case of Poisson integrals.

## References

1. O. Kallenberg, Exchangeable random measures in the plane, University of North Carolina Center for Stochastic Processes Technical Report No. 240, Sept. 1988.
2. O. Kallenberg and J. Szulga, Multiple integration with respect to Poisson and Lévy processes, University of North Carolina Center for Stochastic Processes Technical Report No. 224, Feb. 1988. Prob. Theor. Rel. Fields, 1989, to appear.

RAJEEVA L. KARANDIKAR

Professor Karandikar worked jointly with G. Kallianpur on nonlinear filtering. A book on the subject by Kallianpur and Karandikar has just been published [1]. It is an expanded and improved version of the white noise theory developed over the last five years. Two new features (the results of new research) which have either not been reported, or not adequately described in previous reports are the following.

1. Smoothness properties of the conditional expectation in finitely additive white noise filtering [2]. It is shown that for a wide class of signal processes and bounded  $g$ , the conditional expectation  $\Pi(g,y)$  in the white noise filtering model is a  $C^\infty$ -functional of the observations in the sense that  $\pi(g,y)$  and its Frechét derivatives (which exist) are random variables (called "accessible") on the quasicylindrical probability space on which the observation model is defined. This solves the problem posed to Kallianpur by Professor P. Malliavin some years ago.

2. Statistical applications of the white noise theory are briefly discussed in [1, Chapter XI]. These include parameter estimation in linear models, likelihood ratio and signal detection and the filtering problem for countable state Markov processes.

References

1. G. Kallianpur and R.L. Karandikar, White Noise Theory of Prediction, Filtering and Smoothing (1988), Gordon and Breach Science Publishers
2. H.P. Hucke, G. Kallianpur and R.L. Karandikar, Smoothness properties of the conditional expectation in finitely additive white noise filtering, University of North Carolina Center for Stochastic Processes Technical Report No. 221, Jan. 88., J. Multivariate Anal., 1988, to appear.

## ANNA LAWNICZAK

Professor Lawniczak worked on the ergodic properties of certain nonGaussian processes (jointly with S. Cambanis) and also on certain critical fluctuations in stochastic interacting particle systems.

1. Ergodic properties of stationary infinitely divisible processes [1].

We derive spectral necessary and sufficient conditions for stationary symmetric infinitely divisible processes to be ergodic and mixing. We have shown that most (and we still hope to show that all) infinitely divisible processes with a harmonic spectral representation are not ergodic. Therefore they are distinct from the infinitely divisible moving averages, which are always mixing. This is in sharp contrast with the Gaussian case where all moving averages have a harmonic spectral representation.

2. Critical fluctuations in interacting particle systems [2].

In stochastic interacting particle systems (cellular automata), the deviations from the purely macroscopic hydrodynamical regime, which is described by "small fluctuation fields", might cause macroscopic effects in critical cases. When the limiting deterministic evolution has unstable (resp. neutral) directions, some small fluctuations might be amplified (resp. grow) and become macroscopically finite after suitably long times. We discuss such phenomena on a mathematical basis by analysing some simple models of stochastic interacting particle systems. We observe that (1) the critical phenomena have their own time scale; (2) at finite times (in such a scale) the law of large numbers no longer holds (even locally) and the state of the system is not described by a single profile but rather by a distribution law on such profiles; (3) the

evolution to such law is either a statistical (measure valued) solution of the original macroscopic equation or it is ruled by a stochastic partial differential equation.

Specifically, we consider a one dimensional system of  $\pm 1$  spins whose dynamics are determined by the sum of two generators, one describing a spin flip, Glauber process and the other a Kawasaki (Hirring) evolution. It has been proved that if the Kawasaki dynamics are suitably speeded up (like  $\epsilon^{-2}$ ,  $\epsilon \rightarrow 0$ ), then in the continuous limit ( $\epsilon \rightarrow 0$ ) propagation of chaos holds and the local magnetization satisfies a reaction-diffusion equation, whose instantaneous solution we investigate. In this case we have a stationary solution to the macroscopic equation which in the profile space belongs to a stable "manifold"  $M$  of stationary points obtained by rigid space shifts of the stationary solution. Furthermore the direction along this manifold is neutral for the evolution. We expect that the role of microscopic fluctuations in this case becomes relevant in a suitable time scale where the stationary solution starts moving randomly on the manifold  $M$  with the law of some Brownian motion. An analogous situation can be observed when studying the small perturbations of some dynamical systems.

#### References

1. S. Cambanis and A. Lawniczak, Ergodic properties of stationary infinitely divisible processes, University of North Carolina Center for Stochastic Processes Technical Report, in preparation.
2. A. de Masi, A. Lawniczak and E. Presutti, Critical fluctuations in interacting particle systems, University of North Carolina Center for Stochastic Processes Technical Report, in preparation.

## ITARU MITOMA

Professor Mitoma worked jointly with G. Kallianpur on infinite dimensional diffusions and on interacting systems of neurons.

1. Infinite dimensional diffusions (with G. Kallianpur and R. Wolpert) [1].

Diffusions taking values in infinite dimensional spaces occur in such diverse fields as nonlinear filtering, infinite particle systems and population genetics. More specifically this work has been motivated by the study of the motion of random strings and the development of more realistic models for the description of the voltage potential of a spatially extended neuron.

The specific stochastic differential equation (SDE) studied is of the form

$$dX_t = A(t, X_t)dt + B(t, X_t)dW_t$$

where  $W=(W_t)$  is a  $\phi'$ -valued Wiener process and  $\phi'$  is the strong dual of a countably Hilbertian nuclear space  $\phi$ . The coefficient functions  $A: \mathbb{R}_+ \times \phi' \rightarrow \phi$  and  $B: \mathbb{R}_+ \times \phi' \rightarrow \mathcal{L}(\phi', \phi')$  satisfy certain measurability, continuity, coercivity and growth conditions. Using a stochastic Galerkin method, the existence of a solution to the martingale problem and of a weak solution is established. This is a major difference between the present work and other works known to us on infinite dimensional (Banach or Hilbert space valued) SDE's (such as the work of Krylov and Rozovskii). The monotonicity condition is used only to prove uniqueness, using a Yamada-Watanabe type argument.

2. Fluctuation theorems for large systems of interacting (infinite dimensional) diffusions (with G. Kallianpur) [2].

Large assemblies of neurons interact in complicated ways. One such model of interactions is studied yielding a central limit theorem for such large

systems. It is shown that the weak solution of a Langevin-type stochastic differential equation exists uniquely on a space of generalized functionals which is an appropriate model for the central limit theorem for an interacting system of spatially extended neurons.

The Langevin-type SDE in question is of the form

$$dX(t) = L^*(t)X(t)dt + dW(t)$$

where  $L$  is formally a second order differential operator. A generalized solution of the above SDE is a stochastic process which is a continuous linear functional on a class  $\mathfrak{D}_\phi$  of smooth functionals on  $\phi'$  (dual of a nuclear space  $\phi$ ). For each  $F \in \mathfrak{D}_\phi$ ,  $W_F(t)$  is a continuous, additive Gaussian process. The notion of a generalized solution is defined and its existence is proved under suitable conditions.

The work is related to some recent work of J.D. Deuschel. The research opens up a class of new problems dealing with fluctuation theorems for different kinds of interactions in particle systems as well as neuronal systems.

#### References

1. G. Kallianpur, I. Mitoma, R.L. Wolpert, Diffusion equations in duals of nuclear spaces, University of North Carolina Center for Stochastic Processes Technical Report No. 234, July 88.
2. G. Kallianpur and I. Mitoma, A Langevin-type stochastic differential equation on a space of generalized functionals, University of North Carolina Center for Stochastic Processes Technical Report No. 238, Aug. 88.

**ECKHARD PLATEN**

Dr. Platen's research is a continuation of his study of the exclusion process in a random medium and investigates its macroscopic nonequilibrium dynamics.

On a wide range exclusion process in a random medium with local jump intensity  
[1].

Based on a law of large numbers and the specific properties of the exclusion dynamics it is shown under suitable assumptions that the particle concentration follows a nonlinear evolution equation. The present work is motivated by the problem of stochastic charge transport.

**Reference**

1. E. Platen, On a wide range exclusion process in a random medium with local jump intensity, University of North Carolina Center for Stochastic Processes Technical Report No. 236, Aug. 1988.

## TOMASZ ROLSKI

Dr. Rolski conducted joint research with D.J. Daley on problems in queueing theory. Their work on approximations in light traffic for queues is summarized as follows:

Light traffic approximation in queues [1].

For a stationary waiting time random variable  $W \equiv W(S,T)$  in a GI/G/1 queueing system with generic service and inter-arrival time random variables  $S$  and  $T$  respectively, with  $ES < ET$ , performance characteristics including  $\Pr\{W > 0\}$  and  $EW$  are studied in light traffic conditions. One way of attaining these conditions, as considered in a previous paper, is to replace  $T$  by  $\gamma T$  for large  $\gamma$ ; another way is to thin the arrival process with small but positive retention probability  $\pi$ . These two approaches are compared, the thinning approach being applied to queues with either a renewal or a periodic Poisson arrival process. Results are also given for GI/M/k and GI/D/k queues. The variety of queueing systems studied is reflected in the different behaviour both of the quantities calculated directly and of the derived quantity  $E(W|W > 0)$ . The dominant feature of light traffic characteristics is their dependence on the clustering tendency and related properties of the arrival process.

## Reference

1. D.J. Daley and T. Rolski, Light traffic approximation in queues (II), University of North Carolina Center for Stochastic Processes Technical Report No. 233, May 88.

## RICHARD L. SMITH

During a three month visit Professor Smith studied several areas in extreme value theory for dependent sequences. In particular work was reported on the use of the Stein-Chen Poisson approximation method for extreme values, and on a counterexample regarding the so-called extremal index of a stationary sequence. This work is summarized below.

1. Extreme value theory for dependent sequences via the Stein-Chen method of successive approximation [1].

In 1970 Stein introduced a new method for bounding the approximation error in central limit theory for dependent variables. This was subsequently developed by Chen for Poisson approximation and has proved very successful in the areas to which it has been applied. Here it is shown how the method can be applied to extreme value theory for dependent sequences, focussing particularly on the nonstationary case. The method gives new and shorter proofs of some known results, with explicit bounds for the approximation error.

2. A counterexample concerning the extremal index [2].

The concept of an extremal index, which is a measure of local dependence amongst the exceedances over a high threshold by a stationary sequence, has a natural interpretation as the reciprocal of mean cluster size. We exhibit a counterexample which shows that this interpretation is not necessarily correct.

Previous work on approximation in extreme value theory was completed and a summary follows:

### 3. Approximations in extreme value theory [3].

Following a survey of rates of convergence in extreme value theory, a new class of approximations is developed and compared with existing approximations based on the extreme value distributions. Convergence in Hellinger distance is established, this distance measure being chosen because of its statistical applications. Numerical examples confirm the superiority of the new approximation.

#### References

1. R.L. Smith, Extreme value theory for dependent sequences via the Stein-Chen method of successive approximation, University of North Carolina Center for Stochastic Processes Technical Report No. 213, Oct. 1987.
2. R.L. Smith, A counterexample concerning the extremal index, University of North Carolina Center for Stochastic Processes Technical Report No. 237, Aug. 1988.
3. R.L. Smith, Approximations in extreme value theory, University of North Carolina Center for Stochastic Processes Technical Report No. 205, Sept. 1987.

**ERIC WILLEKENS**

One of Dr. Willekens' main areas of interest concerns the important so-called "subexponential" distributions. During his visit Dr. Willekens investigated a yet wider class of distributions defined by asymptotic relations for their tail functions. In particular the research concentrated on estimating tail properties and the use of the estimator in determining whether a member of the wider class is, in fact, subexponential. A summary of the work follows.

Estimation of convolution tails [1].

Several classes of distribution functions (d.f.) are obtained by considering distributions whose tailfunctions satisfy special asymptotic relations. A large class sharing this property is provided by the subexponential class  $\mathcal{S}$ , in which case the asymptotic relation involves tails of convolution powers. This paper introduces a statistic which estimates the asymptotic behaviour of convolution tails of a given d.f. and it is shown that this statistic is strongly consistent and asymptotically normal under appropriate conditions. Furthermore, the statistic can be used to test the hypothesis that a d.f. is in  $\mathcal{S}$ .

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1. E. Willekens, Estimation of convolution tails, University of North Carolina Center for Stochastic Processes Technical Report No. 206, Sept. 87.

## RESEARCH IN STATISTICAL INFERENCE

RAYMOND J. CARROLL

During the past year, we continued to work on variance function estimation, data transformation and measurement error models. We also made contributions in the area of nonparametric smoothing techniques and multiple use calibration in chemistry. New report titles and their abstracts follow.

1. An asymptotic theory for weighted least squares with weight estimated by replication (with D.B.H. Cline).

We consider a heteroscedastic linear regression model with replication. To estimate the variances, one can use the sample variances or the sample average squared errors from a regression fit. We study the large sample properties of these weighted least squares estimates with estimated weights when the number of replicates is small. The estimates are generally inconsistent for asymmetrically distributed data. If sample variances are used based on  $m$  replicates, the weighted least squares estimates are inconsistent for  $m = 2$  replicates even when the data are normally distributed. With between 3 and 5 replicates, the rates of convergence are slower than the usual square root of  $N$ . With  $m \geq 6$  replicates, the effect of estimating the weights is to increase variances by  $(m-5)/(m-3)$ , relative to weighted least squares estimates with known weights.

2. Optimal rates of convergence for deconvolving a density (with P. Hall)

Suppose we observe the sum of two independent random variables  $X$  and  $Z$  where  $Z$  denotes measurement error and has a known distribution, and where the unknown density  $f$  of  $X$  is to be estimated. It is shown that if  $Z$  is normally distributed and if  $f$  has  $k$  bounded derivatives, then the fastest attainable

convergence rate of any nonparametric estimator of  $f$  is only  $(\log n)^{-k/2}$ . Therefore deconvolution with normal errors may not be a practical proposition. Other error distributions are also treated. Stefanski-Carroll (1987b) estimators achieve the optimal rates. Our results have versions for multiplicative errors, where they imply that even optimal rates are exceptionally slow.

3. Variance function estimation in regression: The effect of estimating the mean  
(with P. Hall)

We consider estimation of a variance function  $g$  in regression problems. Such estimation requires simultaneous estimation of the mean function  $f$ . We obtain sharp results on the extent to which the smoothness of  $f$  influences best rates of convergence for estimating  $g$ . For example, in nonparametric regression with two derivatives on  $g$ , "classical" rates of convergence are possible if and only if the unknown  $f$  satisfies a Lipschitz condition of order  $1/3$  or more. If a parametric model is known for  $g$ , then  $g$  may be estimated  $n^{1/2}$ -consistently if and only if  $f$  is Lipschitz of order  $1/2$  or more. Optimal rates of convergence are attained by kernel estimators.

4. A note on second order effects in a semiparametric context (with W. Härdle)

We consider a heteroscedastic linear regression model with normally distributed errors in which the variances depend on an exogenous variable. Suppose that the variance function can be parameterized as  $\psi(z_1, \theta)$  with  $\theta$  unknown. If  $\hat{\theta}$  is any root- $N$  consistent estimate of  $\theta$  based on squared residuals, it is well known that the resulting generalized (weighted) least squares estimate with estimated weights has the same limit distribution as if  $\theta$  were known. The covariance of this estimate can be expanded to terms of order  $N^{-2}$ . If the variance function is unknown but smooth, the problem is adaptable, i.e., one can estimate the variance function nonparametrically in such a way

that the resulting generalized least squares estimate has the same first order normal limit distribution as if the variance function were completely specified. In a special case we compute an expansion for the covariance in this semiparametric context, and find that the rate of convergence is slower for this estimate than for its parametric counterpart. More importantly, we find that there is an effect due to how well one estimates the variance function. We use a kernel regression estimator, and find that the optimal bandwidth in our problem is of the usual order, but that the constant depends on the variance function as well as the particular linear combination being estimated.

#### 5. A note on extended quasi-likelihood (with M. Davidian)

We study the method of extended quasi-likelihood estimation and inference of a variance function recently proposed by Nelder & Pregibon (1987). The estimates are inconsistent in general, and the test levels can be biased, but in many cases such as the exponential family the inconsistency and bias will not be a major concern. Extended quasi-likelihood is compared with Carroll & Ruppert's (1982) pseudo-likelihood method, which gives consistent estimates and, when slightly modified, asymptotically unbiased tests. We quantify the notion of a problem in which the amount of statistical information is large in each unit, showing in this instance that the two estimates are closely related and may be asymptotically equivalent in many important cases. However, in some cases outside the exponential family, an asymptotic bias can persist.

#### 6. Nonparametric estimation of optimal performance criteria in quality engineering (with P. Hall)

Box (1987) and Leon et al. (1987) discuss the problem of closeness to target in quality engineering. If the mean response  $f(x,z)$  depends on  $(x,z)$ , the variance function is a PERMIA if it is  $g(z)$ , i.e., depends only on  $z$ . The goal is to find  $(x_0, z_0)$  which minimizes variance while achieving a target mean

value. We pose and answer the question: for given smoothness assumptions about  $f$  and  $g$ , how accurately can we estimate  $x_0$  and  $z_0$ ? As part of the investigation, we also find optimal rates of convergence for estimating  $f$ ,  $g$  and their derivatives.

#### 7. Variance functions and the minimum detectable concentration in assays

(with M. Davidian and W. Smith)

Assay data are often fitted by a nonlinear regression model incorporating heterogeneity of variance. Typically, the standard deviation of the response is taken to be proportional to a power  $\alpha$  of the mean. There is considerable empirical evidence suggesting that for assays of a reasonable size, how one estimates the parameter  $\theta$  does not greatly affect how well one estimates the mean regression function. An additional component of assay analysis is the estimation of auxiliary constructs such as the minimum detectable concentration, for which many definitions exist; we focus on one such definition. The minimum detectable concentration depends both on  $\theta$  and the mean regression function. We compare standard methods of estimating the parameter  $\theta$  due to Rodbard (1978), Raab (1981a), Sadler and Smith (1985) and Carroll and Ruppert (1982b). When duplicate counts are taken at each concentration, the first method is only 20% efficient asymptotically in comparison to the fourth for normal data, and in an example the resulting estimate of the minimum detectable concentration is asymptotically 3.7 times more variable. Less dramatic results obtain for the second and third estimators compared to the fourth. Simulation results and an example support the asymptotic theory. The results have implications in applications other than the assay problem in which heterogeneity of variance and issues of calibration arise.

#### 8. A quick and easy multiple use calibration curve procedure (with J. Sacks and C. Spiegelman)

The standard multiple use calibration procedure due to Scheffe (1973) states that with probability  $1-\delta$ , the proportion of calculated confidence intervals containing the true unknowns is at least  $1-\alpha$  in the long run. The probability  $1-\delta$  refers to the probability that the calibration experiment results in a 'good' outcome. In Scheffe's formulation a good outcome involves both coverage of the true underlying regression curve and an upper confidence limit for  $\sigma$ , the scale parameter. Scheffe's procedure is fairly difficult for practitioners to apply because it relies on tables that are not easy to use. A simple notion of 'goodness' which only requires the calibration experiment to result in coverage of the underlying regression leads to easily calculated confidence intervals for the unknowns. In addition, these intervals are generally shorter than Scheffe's. An application example is given to illustrate the technique.

#### 9. Covariance analysis in generalized linear measurement error models

We summarize some of the recent work on the errors-in-variables problem in generalized linear models. The focus is on covariance analysis, and in particular testing for an estimation of treatment effects. There is a considerable difference between the randomized and nonrandomized models when testing for an effect. For estimation, one is largely reduced to using an errors in variables analysis. Some of the possible methods are outlined and compared.

#### 10. Symmetrized nearest neighbor regression estimates

We consider univariate nonparametric regression. Two standard nonparametric regression function estimates are kernel estimates and nearest neighbor estimates. Mack (1981) noted that both methods can be defined with respect to a kernel or weighting function, and that for a given kernel and a suitable choice of bandwidth, the optimal mean squared error is the same

asymptotically for kernel and nearest neighbor estimates. Yang (1981) defined a new type of nearest neighbor regression estimate using the empirical distribution function of the predictors to define the window over which to average. This has the effect of forcing the number of neighbors to be the same both above and below the value of the predictor of interest; we call these symmetrized nearest neighbor estimates. The estimate is a kernel regression estimate with "predictors" given by the empirical distribution function of the true predictors. We show that for estimating the regression function at a point, the optimum mean squared error of this estimate differs from that of the optimum mean squared error for kernel and ordinary nearest neighbor estimates. No estimate dominates the others. They are asymptotically equivalent with respect to mean squared error if one is estimating the regression function at a mode of the predictor.

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- N. Nandagopalan, Some results in extreme value theory for stationary random processes.
- R. Selukar, On estimation of Hilbert space valued parameters.
- W. Wu, Stable processes: representation, regression, random filtering and the bootstrap.

## MANUSCRIPTS

- R.J. Carroll and D.B.H. Cline, An asymptotic theory for weighted least squares with weight estimated by replication, submitted for publication.
- R.J. Carroll and P. Hall, Optimal rates of convergence for deconvolving a density, submitted for publication.
- R.J. Carroll and P. Hall, Variance function estimation in regression: The effect of estimating the mean, submitted for publication.
- R.J. Carroll and W. Härdle, A note on second order effects in a semiparametric context, submitted for publication.
- R.J. Carroll and M. Davidian, A note on extended quasi-likelihood, submitted for publication.
- R.J. Carroll and P. Hall, Nonparametric estimation of optimal performance criteria in quality engineering, submitted for publication.
- R.J. Carroll, M. Davidian and W. Smith, Variance functions and the minimum detectable concentration in assays, submitted for publication.
- R.J. Carroll, J. Sacks and C. Spiegelman, A quick and easy multiple use calibration curve procedure, submitted for publication.
- R.J. Carroll, Covariance analysis in generalized linear measurement error models, submitted for publication.
- R.J. Carroll, Symmetrized nearest neighbor regression estimates, submitted for publication.

## STOCHASTIC PROCESSES SEMINARS

- Sept. 3 Poisson driven, nuclear space valued stochastic differential equations, G. Hardy, University of Minnesota
- Sept. 9 Subexponential distributions and their role in the tail behaviour of compound laws, E. Willekens, Catholic University of Leuven
- Sept. 16 Diffusions and random walks in random media, G. Papanicolau, Courant Institute of Mathematics and Science
- Sept. 23 Nuclear space valued Ornstein-Uhlenbeck processes, L. Gorostiza, Central National University of Mexico
- Sept. 30 Measure-valued branching diffusion and its set-valued support processes, D. Dawson, Carleton University
- Oct. 7 Progress in stochastic control, V.E. Benes, AT&T Bell Laboratories
- Oct. 14 Domains of attraction for a family of processes between suprema and sums, P. Greenwood, University of British Columbia
- Oct. 21 Estimating extreme quantiles, R.L. Smith, University of Surrey
- Oct. 27 Designs for computer experiments. II, J. Sacks, University of Illinois
- Nov. 2 Inference after a stopping time, J. Bather, University of Sussex
- Nov. 5 On path properties of certain infinitely divisible processes, J. Rosinski, University of Tennessee
- Nov. 10 Hellinger processes and convergence of statistical experiments, J. Jacod, University of Paris VI
- Nov. 11 Function minimization on the basis of noisy samples, with applications to machine learning, S. Yakowitz, University of Arizona
- Nov. 18 Higher order crossings theory and practice, B. Kedem, University of Maryland
- Dec. 2 Two optimal stopping problems, Y.-C. Yao, Colorado State University
- Dec. 10 Consistent order determination for processes with infinite variance, R.J. Bhansali, University of Liverpool and Texas A&M University
- Dec. 11 Weak solutions of stochastic evolution equations, M. Metivier, Ecole Polytechnique, Paris
- Dec. 17 Ergodic properties of almost periodic Poisson processes, T. Rolski, University of Wroclaw
- Jan. 21 Feynman's paper revisited, G. Johnson, University of Nebraska
- Jan. 25 A classification of harmonizable processes, M.M. Rao, University of California, Riverside

- Feb. 24 On the non equilibrium dynamics of a stochastic interacting particle system, E. Platen, Academy of Sciences of the GDR
- Feb. 25 Estimation of intensity functions of Poisson processes via the method of sieves, with application to positron emission tomography, A.F. Karr, The Johns Hopkins University
- Mar. 2 Strongly harmonizable almost periodically correlated processes, H.L. Hurd, AT&T
- Mar. 16 The computation of stationary distributions of Markov chains through perturbations, J.J. Hunter, University of Auckland
- Mar. 23 Limit theorems and long-range dependence, M. Rosenblatt, University of California, San Diego
- Mar. 30  $V$ -boundedness and  $L^{2,p}$ -boundedness of stochastic processes, C. Houdré, McGill University and University of North Carolina
- Apr. 8 Quantiles: Edgeworth expansion and coverage accuracy, P. Hall, Australian National University
- Apr. 14 The maximum spacing method, B. Ranneby, Swedish University of Agricultural sciences
- Apr. 15 Banach groups and the unification of operator theory and measure theory, P. Masani, University of Pittsburgh
- Apr. 26 Sojourn times in a cone for a class of vector Gaussian processes, S. Berman, New York University
- May 18 On the linear prediction of multivariate  $V$ -bounded processes, C. Houdré, McGill University and University of North Carolina
- May 26 Problems on random graphs, P. Whittle, Cambridge University
- May 31 Strong law of large numbers with applications to linear regression, M. Musiela, University of New South Wales
- July 14 Statistics of extreme values, L. de Haan, Erasmus University
- July 19 Multiple integration with respect to symmetric Lévy processes, O. Kallenberg, Auburn University
- July 25 Large deviations for maximum local time of stable Lévy processes, M. Lacey, University of North Carolina
- Aug. 22 Malliavin calculus approach to stochastic integration, A. Russek, Louisiana State University
- Aug. 24 Fluctuations in a nonlinear reaction-diffusion model, P. Kotelenez, University of Utrecht
- Aug. 25 Marked random counting measures for geometrical structures and their characteristics and estimators, D. König, Mining Academy of Freiberg
- Aug. 29 Interacting diffusions and symmetric statistics, R. Adler, Technion

## LIST OF PROFESSIONAL PERSONNEL

1. Faculty Investigators:

S. Cambanis  
 R.J. Carroll  
 G. Kallianpur  
 M.R. Leadbetter

2. VisitorsSenior:

J. Bather	University of Sussex	Sept. - Dec. 87
D. Dawson	Carleton University	Sept. 87
L. de Haan	Erasmus University	June - July 88
L. Gorostiza	Central National Univ. of Mexico	Sept. 87
J.J. Hunter	Auckland University	Jan. 88 - Mar. 88
G. Johnson	University of Nebraska	Nov. 87 - Apr. 88
O. Kallenberg	Auburn University	July - Aug. 88
R.L. Smith	University of Surrey	Sept. - Nov. 87

Junior:

M.T. Alpuim	University of Lisbon	Sept. - Nov. 87
G. Hardy	University of Minnesota	Sept. - Dec. 87
C. Houdré	McGill University	Sept. 87 - June 88
R. Karandikar	Indian Statistical Institute	Nov. - Dec. 87
A. Lawniczak	University of Toronto	Mar. - Aug. 88
I. Mitoma	Hokkaido University	Sept. 87 - Aug. 88
E. Platen	Academy of Science of the GDR	Feb. 88
T. Rolski	University of Wroclaw	Nov. - Dec. 87.
E. Willekens	Catholic University of Leuven	Sept. 87

3. Graduate Students

D. Baldwin  
 K. Benhenni  
 M. Marques  
 N. Nandagopalan  
 R. Selukar  
 W. Wu

## Ph.D DEGREES AWARDED

G. Hardy	Stochastic differential equations in duals of nuclear spaces	Nov. 87
M. Marques	A study of Lebesgue decomposition of measures induced by stable processes	Nov. 87
Y. Shen	Edgeworth expansion in tests concerning heteroscedasticity	Jan. 88

## IN PREPARATION

D. Baldwin	Robust inference for infinite dimensional parameters	1989
K. Benhenni	Sampling designs and estimators for approximating integrals of time series	1989
N. Nandagopalan	Some results in extreme value theory for stationary random processes	1989
R. Selukar	On estimation of Hilbert space valued parameters	1988
W. Wu	Stable processes: representation, regression, random filtering and the bootstrap	1989

## INTERACTIONS

S. Cambanis was awarded an Honorary Doctorate by the University of Athens, Greece. He was an invited speaker at Mathematics Day, University of Athens, and at the Madison meeting of the Institute of Mathematical Statistics. He gave seminars at Michigan State University, Courant Institute, University of Maryland, University of Pittsburgh and Columbia University. He gave talks at the 17th Conference on Stochastic Processes and their Applications in Rome, and the Symposium on Probability and its Applications at the annual meeting of the Institute of Mathematical Statistics in Fort Collins, CO. He completed his term as Associate Editor for Stochastic Processes of the IEEE Transactions on Information Theory and continued serving as an editorial board member of the SIAM Journal on Applied Mathematics. He was elected member of the Committee on Stochastic Processes and their Applications of the Bernoulli Society for Mathematical Statistics and Probability and was appointed to the National Science Foundation - Conference Board of the Mathematical Sciences Regional Conference Panel.

R.J. Carroll was selected as the editor of the Journal of the American Statistical Association, Theory and Methods Section for 1988-90. He has accepted a position as professor and Head of the Statistics Department at Texas A&M University. He spent the month of November at the University of Bonn working with Dr. W. Härdle on topics in nonparametric smoothing techniques. He presented invited talks at the NIH conference on Errors in Variables, the University of Bonn, the University of Dortmund, the University of Michigan, the University of Texas at Austin, the University of Texas at San Antonio, the Southern Methodist University, the ENAR spring meeting of the Biometric Society, the Merrell Dow Research Institute, and the SREB summer conference.

G. Kallianpur was an invited speaker at the 20th Symposium on the Interface: Computing Science and Statistics in Washington, at the Conference on Function Space Integration at the University of Antwerp, Belgium, and at the Second Workshop on Stochastic Analysis in Siliviri, Turkey. He gave seminars at University of Minnesota, Université de Montréal, Mathematical Centre in Amsterdam, Twente University and University of Utrecht. The seminars in Holland were given while he was a guest of the Dutch Mathematical Society. He continued to serve as Editor of Applied Mathematics and Optimization, Sankhyā (with C.R. Rao and J.K. Ghosh) and the Journal of Multivariate Analysis, and as Associate Editor of Stochastic Processes and Their Applications.

M.R. Leadbetter gave an invited paper at the Symposium on Probability and its Applications associated with the annual meeting of the Institute of Mathematical Statistics in Fort Collins, CO, and at the Conference on Extreme Values in Oberwolfach, W. Germany. He was a principal speaker at the Probability Symposium held with regional American Mathematical Society meetings at Knoxville, TN, and gave seminars at Lund University, Sweden. He participated in program reviews for the ONR probability and statistics program and has agreed to be a member of their review Board of Visitors. He also continued his service as Associate Editor of the Annals of Probability.

M. Teresa Alpuim gave a talk at the 16th Conference on Stochastic Processes and their Applications at Stanford University.

John Bather gave seminars at Florida State University, Columbia University and the Operations Research Department of UNC.

K. Benhenni gave a talk at the Symposium on Probability and Its Applications at the annual meeting of the Institute of Mathematical Statistics in Fort Collins.

CO, and seminars at Bell Laboratories and New York University.

C. Houdré attended the 4th Annual Cornell Summer Workshop on Systems, Control, and Communication at Cornell University where he gave a talk.

J.J. Hunter gave seminars at University of California, Santa Barbara, University of Arizona and Virginia Polytechnic Institute.

G. Johnson gave talks at the University of Missouri at Columbia, University of Missouri at Rolla, University of Minnesota and the College of St. Thomas.

O. Kallenberg presented a paper at the Symposium on Probability and its Applications at the annual meeting of the Institute of Mathematical Statistics in Fort Collins, CO.

A. Lawniczak gave a seminar at the University of Toronto.

I. Mitoma gave seminars at University of California Los Angeles, Université de Paris VI, Ecole Polytechnique, Université de Clermont-Ferrand and Carleton University.

S. Nandagopalan attended the annual meeting of the Institute of Mathematical Statistics and the Symposium on Probability and Its Applications in Fort Collins, CO.

Tomasz Rolski gave a seminar at the Bell Laboratories in Murray Hill, NJ.

R. Selukar gave a seminar at the University of California, Santa Barbara.

R.F. Serfozo gave seminars at the annual material handling research forum at Georgia Tech and the AMS meeting in University of Utah, Logan.

R.L. Smith gave seminars at Texas A&M University, University of Texas at Austin, George Washington University, Cornell, Boston University and University of Pennsylvania.