AD-A266 112

(2)

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED FINAL/01 JUL 92 TO 30 JUN 93

4. TITLE AND SUBTITLE WORKSHOP ON CYCLOSTATIONARY SIGNALS (U)	5. FUNDING NUMBERS 2304/ES F49620-92-J-0303
6. AUTHOR(S) Dr. William A. Gardner	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California Electrical Eng/Computer Science Davis CA 95616-5294	8. PERFORMING ORGANIZATION REPORT NUMBER AFOSR-TR- 93 0413
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 110 DUNCAN AVE, SUTE B115 BOLLING AFB DC 20332-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-92-J-0303
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED	12b. DISTRIBUTION CODE UL

13. ABSTRACT (Maximum 200 words)

The Workshop on Cyclostationary Signals was organized and chaired by the Principal Investigator, and was held August 16-18, 1992 at the Napa Valley Lodge in Yountville, CA. There were 63 participants, four of whom gave plenary lectures, and 32 of whom presented poster papers. There was good representation from academia, industry, and the government, and from engineering and applied mathematics disciplines. Generally the mood was one of considerable enthusiasm and the majority of participants recommended a second workshop in one to two years.

14. SUBJECT TERMS			15. NUMBER OF PAGES 50
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR(SAME AS REPORT)

FINAL REPORT

for the

WORKSHOP ON CYCLOSTATIONARY SIGNALS

Sponsored by

NATIONAL SCIENCE FOUNDATION (GRANT # MIP-91-12800)
ARMY RESEARCH OFFICE (GRANT # DAAL03-92-G-0297)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (GRANT # F49620-92-J-0303)
OFFICE OF NAVAL RESEARCH (GRANT # N0001492-J-1218)

PRINCIPAL INVESTIGATOR: WILLIAM A. GARDNER

The Workshop on Cyclostationary Signals was organized and chaired by the Principal Investigator, and was held August 16-18, 1992 at the Napa Valley Lodge in Yountville, California. There were 63 participants, four of whom gave plenary lectures, and 32 of whom presented poster papers. There was good representation from academia, industry, and the government, and from engineering and applied mathematics disciplines. Generally the mood was one of considerable enthusiasm and the majority of participants recommended a second workshop in one to two years.

The purpose of the workshop, descriptions of the plenary lectures, and summaries of the poster papers are contained in the Proceedings, which also contains a list of participant names, affiliations, mailing addresses, and phone numbers. The Proceedings are attached hereto.

All participants received copies of the Proceedings, and they all will also receive copies of the IEEE Press volume *Cyclostationarity in Communications and Signal Processing*, which is currently in press. This edited volume contains four tutorial chapters paralleling the four plenary lectures given at the workshop, and it contains ten survey-type articles by poster-paper presenters and others. A copy of the Table of Contents and Introduction for this book are included herewith in an appendix to this report.

The Principal Investigator expresses his gratitude to the sponsoring agencies for making this successful workshop possible.

CYCLOSTATIONARITY IN COMMUNICATIONS AND SIGNAL PROCESSING

EDITED BY
WILLIAM A. GARDNER
UNIVERSITY OF CALIFORNIA, AND
STATISTICAL SIGNAL PROCESSING, INC.

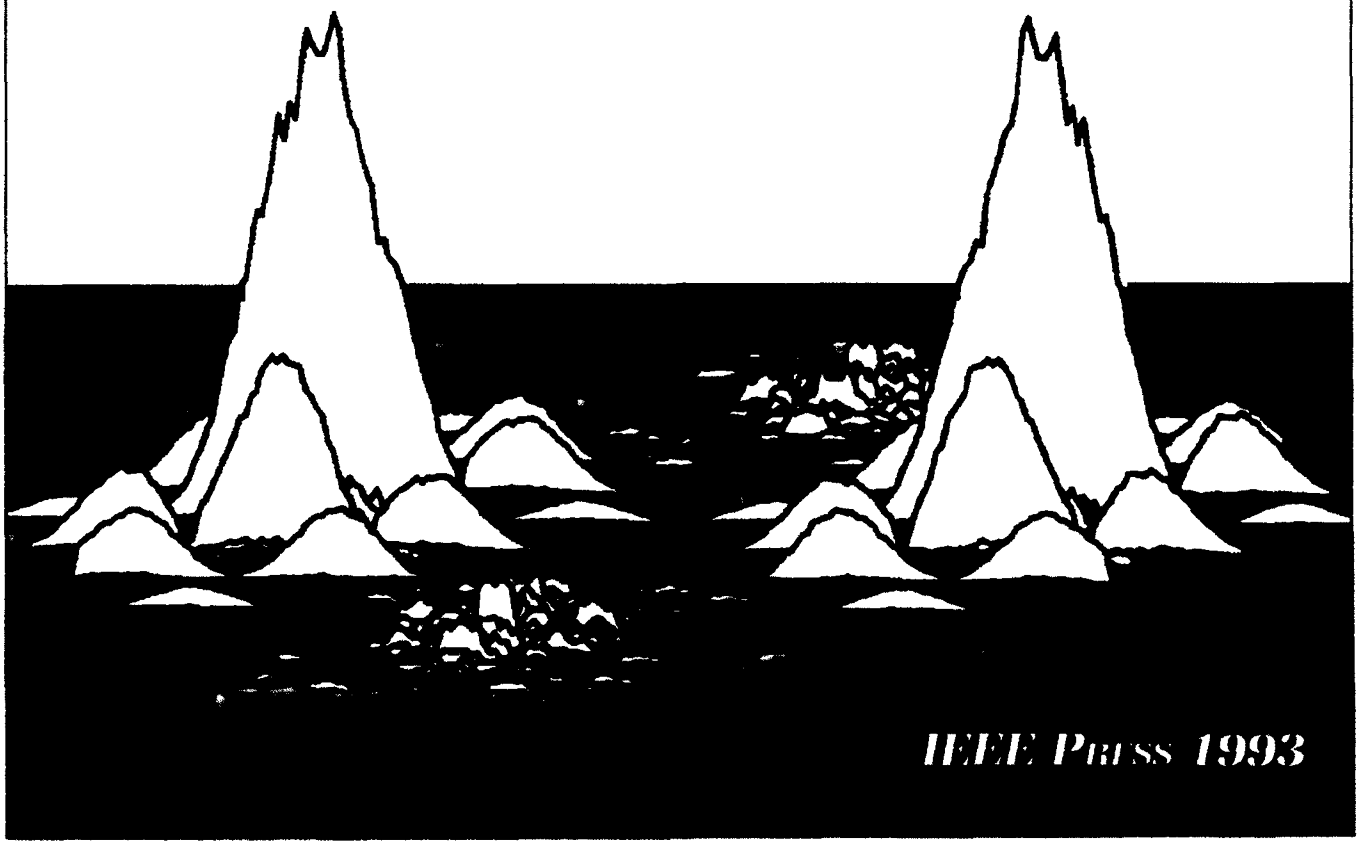


TABLE OF CONTENTS

PART I (Chapters)

PART II (Articles)

EDITOR'S INTRODUCTION

Many conventional statistical signal processing methods treat random signals as if they were statistically stationary, that is, as if the parameters of the underlying physical mechanisms that generate the signals do not vary with time. But for most manmade signals encountered in communication, telemetry, radar, and sonar systems, some parameters do vary periodically with time. In some cases even multiple incommensurate (not harmonically related) periodicities are involved. Examples include sinusoidal carriers in amplitude, phase, and frequency modulation systems, periodic keying of the amplitude, phase, or frequency in digital modulation systems, and periodic scanning in television, facsimile, and some radar systems, and periodic motion in rotating machinery. Although in some cases these periodicities can be ignored by signal processors, such as receivers which must detect the presence of signals of interest, estimate their parameters, and/or extract their messages, in many cases there can be much to gain in terms of improvements in performance of these signal processors by recognizing and exploiting underlying periodicity. This typically requires that the random signal be modeled as *cyclostationary* or, for multiple periodicities, *polycyclostationary*, in which case the statistical parameters vary in time with single or multiple periods. Cyclostationarity also arises in signals of natural origins, due to the presence of rhythmic, seasonal, or other cyclic behavior. Examples include time-series data encountered in meteorology, climatology, atmospheric science, oceanology, astronomy, hydrology, biomedicine, and economics.

Important work on cyclostationary processes and time-series dates back over three decades, but only recently has the number of published papers in this area shown exponential growth. Fueled by recent advances in applications to communications, signal processing, and time-series analysis that demonstrate the substantial advantages of exploiting cyclostationarity in both design and analysis, the appetite for learning about cyclostationarity among research and development communities in areas such as wireless and cable communications, signals intelligence and covert communications, and modeling and prediction for natural systems (hydrology, climatology, meteorology, oceanology, biology/medicine, economics, etc.) has outgrown the available tutorial literature. This edited book is intended to help fill this void by presenting individual tutorial treatments of the major sub-topics of cyclostationarity and by featuring selected articles that review the latest developments in various specific ar as.

The book is composed of two parts: Part I consists of four chapters that are adapted from the four plenary lectures at the Workshop on Cyclostationary Signals, which was held August 16-18, 1992, at the Napa Valley Lodge in Yountville, California. Part II consists of nine articles by participants of this workshop, and others. The workshop audience was mixed, consisting of mathematical statisticians, engineers, and scientists from academia, industry, and the national government. Consequently, different parts of the chapters and different articles address different segments of this general audience. However, the objective of this book is to have all parts provide useful information for all segments. To meet this objective, Part I is strongly tutorial and provides in-depth surveys of major areas of work. Similarly, Part II, which focuses on more specific topics, also has a tutorial survey flavor. Each of these two parts treats both theory and application.

Chapter 1 provides a historical perspective on cyclostationarity and discusses, in detail, both the practical and mathematical motives for studying cyclostationarity. It also treats the philosophy of aesthetics and utility that underlie alternative conceptual/mathematical frameworks within which theory and method can be developed. The latter half of the chapter surveys the theory and application of wide-sense cyclostationarity, touching on the problems of detection, recognition, source-location, and extraction of highly corrupted signals, and the roles that the spectral-line generation and spectral-redundancy properties of cyclostationarity play in tackling these and other problems. This chapter provides an introduction to cyclostationary signals that serves as a foundation for the rest of the book.

Chapter 2, by L. E. Franks, supplements the material on cyclostationary processes by reviewing the basic theory of periodically and polyperiodically time-varying linear systems. Such systems are extensively employed as filters for processing and modeling cyclostationary signals. Various input/output and state-variable descriptions together with filter structures that are appropriate for implementing the desired response characteristics in both continuous- and discrete-time are discussed. The chapter concludes with a brief discussion and some examples of polyperiodic filtering for waveform extraction.

Chapter 3, by S. V. Schell, provides an overview of sensoı array processing for cyclostationary signals, focusing on adaptive spatial filtering and direction-of-arrival estimation. It briefly describes many recently introduced methods and highlights their advantages and disadvantages relative to each other and to more conventional techniques that ignore cyclostationarity. Applications of cyclostationarity-exploiting methods to both existing problems in array processing and the design of new wireless communication systems are suggested.

Chapter 4, by C. M. Spooner, provides an overview of the recently formulated theory of higher-order temporal and spectral moments and cumulants of cyclostationary time-series. It is shown that the *n*th-order polyperiodic cumulant of a polycyclostationary time-series is the solution to the problem of characterizing the strengths of all sine waves that are produced by multiplying n different delayed versions of the time-series together, with the parts of those sine waves that result from products of sine waves, which may be present in lower-order factors of the *n*th-order product, removed. Thus, the study of higher-order cumulants is motivated by a practical problem that arises in signal processing. The chapter also discusses other motivations for studying the moments and cumulants and provides a historical account of cumulants and their uses. The properties of these statistical functions that render them useful in signal processing are discussed and compared to the properties of similar statistical functions for stationary time-series. Applications of the unique signal-selectivity property of the polyperiodic cumulants to the tasks of weak-signal detection and source location are briefly described.

In the first article in Part II, by S. Roy, J. Yang, and P. S. Kumar, the joint transmitter/receiver optimization problem for multi-user communications is addressed, and a coherent view of system design approaches that include different but related multi-input/multi-output models is presented on the basis of analytical optimization. The present state of knowledge in this area is summarized, and the potential for suppression of cochannel interference that is afforded by the cyclostationarity of the signals is emphasized. The results demonstrate analytically that greatly improved cross-talk rejection is achievable when the spectral correlation property of the cyclostationary signals is properly exploited.

In the second article, by N. M. Blachman, the objective is to provide insight into the nature of the self-noise that is present in the timing wave produced by a square-law synchronizer acting on a cyclostationary pulse-amplitude modulated signal, and to provide a quantitative analysis of the mean square phase jitter in the timing wave. The results obtained show explicitly how the design and performance analysis of the square-law synchronizer is characterized by the spectral correlation function and the fourth-order spectral-moment function of the signal.

The third article, by L. Izzo, A. Napolitano, and L. Paura, provides a tutorial review of recent methods for multipath channel identification. It is shown that by exploiting the signal-selectivity properties of the cyclic autocorrelation function or the associated spectral correlation function, these methods can perform well in severely corruptive noise and interference environments. Several such identification methods are compared in terms of their performance characteristics by analysis and simulation.

The fourth article is in two parts. The first part, by Z. Ding, provides a brief overview of the various approaches to blind channel equalization and identification that have been reported in the literature, and then explains the potential advantages to be gained by exploiting the cyclostationarity of digital-quadrature-amplitude-modulated signals. The theoretical possibility of accomplishing blind identification with the use of only second-order statistics is explained, and a frequency-domain approach is described. In the second part, by L. Tong, G. Xu, and T. Kailath, a time-domain approach is presented and the results of simulations which suggest that convergence can be much more rapid than when cyclostationarity is ignored, thereby necessitating the use of higher-than-second-order statistics. A connection between the frequency-domain and time-domain approaches also is explained.

The fifth article, by H. L. Hurd, surveys the progress that has been made on the performance analysis of estimators for the cyclic autocorrelation function and the cyclic spectrum, or spectral correlation function (*to be completed*).

In the sixth article, by R. S. Roberts, W. A. Brown, and H. H. Loomis, the theory and implementation of digital spectral correlation analysis is reviewed. The performance characteristics and computational requirements of various algorithms based on either time smoothing or frequency smoothing are compared analytically, and two specific implementation studies are briefly presented.

The seventh article, by B. F. Rice, S. R. Smith, and R. A. Threlkeld, presents an approach to designing automatic modulation classifiers for cyclostationary signals. The primary features proposed for use in classification of these signals are derived from the power spectral densities of various nonlinearly transformed versions of the signals. These features, which reveal the presence or absence of spectral lines due to modulation-specific cyclostationarity properties, are processed by a probabilistic neural network which implements the decision process. The results of simulations are briefly summarized.

In the eighth article, by A. Miamee, recent developments in the theory of prediction for cyclostationary processes are briefly reviewed. The fundamental role in the theory played by multivariate stationary representations of univariate cyclostationary processes is explained, and both discrete-time and continuous-time processes are considered.

The ninth and final article, by S. Bittanti, reviews recent progress on the development of state space techniques for periodic ARMA modeling of cyclostationary time-series. (*to be completed*)

The chapters in Part I and articles in Part II collectively cover a wide range of topics in the theory and application of cyclostationarity. We hope that the tutorial style of these contributions coupled with the broad survey and comprehensive reference lists they provide will make this volume instrumental in furthering progress in understanding and using cyclostationarity not only in the fields of communications and signal processing, but in all fields where cyclostationary data arises.

PROCEEDINGS OF THE

WORKSHOP ON CYCLOSTATIONARY SIGNALS

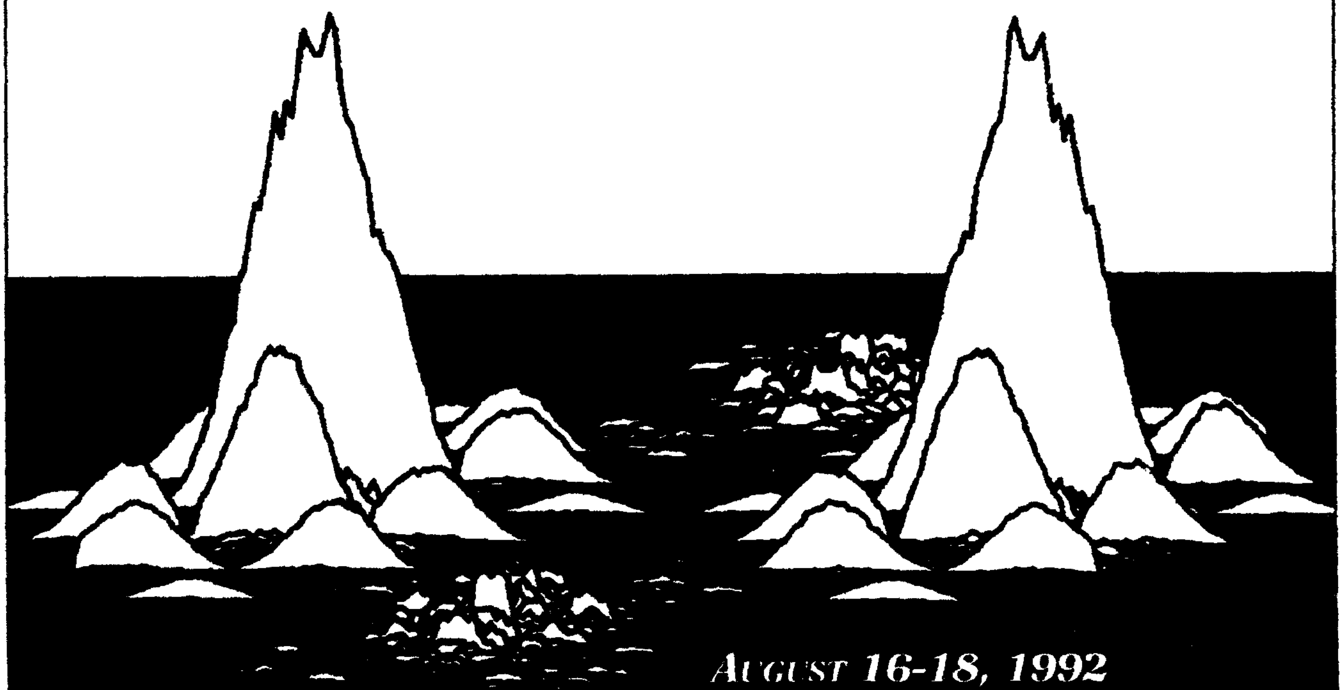
SPONSORED BY:

NATIONAL SCIENCE FOUNDATION

OFFICE OF NAVAL RESEARCH

ARMY RESEARCH OFFICE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH



AUGUST 16-18, 1992

YOUNTVILLE, CALIFORNIA

Proceedings of the Workshop on Cyclostationary Signals

Sponsored by:

National Science Foundation

Office of Naval Research

Army Research Office

Air Force Office of Scientific Research

Workshop Organizer and Chairman:

William A. Gardner

University of California, Davis, *and*

Statistical Signal Processing, Inc.

August 16-18, 1992

Yountville, California

TABLE OF CONTENTS

WORKSHOP STAFF

Workshop Organizer and Chairman

William A. Gardner
Department of Electrical and Computer Engineering
University of California, Davis

Administrative Assistant

Marion T. Franke
Department of Electrical and Computer Engineering
University of California, Davis

Coordinator

Nancy S. Gardner
Statistical Signal Processing, Inc.
Yountville, CA

SPONSORING-AGENCY PROGRAM DIRECTORS

National Science Foundation
Circuits & Signal Processing Program

Dr. John H. Cozzens

Office of Naval Research
Information and Communication Sciences Program

Dr. Rabinder N. Madan

Army Research Office
Information and Signal Processing Program

Dr. James Gault

Air Force Office of Scientific Research
Probability, Statistics, and Signal Processing Program

Dr. Jon A. Sjogren

PREFACE

This proceedings documents the tutorial lectures and poster papers on current research that were presented at the *Workshop on Cyclostationary Signals* held in Yountville, August 16-18, 1992. Summaries of these lectures and papers are given herein. Full presentations of the tutuorial lectures, supplemented by a number of survey/tutorial research papers will appear in the IEEE Press volume, entitled *Cyclostationarity in Communications and Signal Processing,* to be published in 1993. To complement this Proceedings and the edited volume, a collection of reprints of research papers, entitled *Theory and Application of Cyclostationary Signals,* will be published by SSPI publishing in 1993.

PLENARY LECTURE 1

AN INTRODUCTION TO CYCLOSTATIONARY SIGNALS

William A. Gardner
Department of Electrical and Computer Engineering
University of California
Davis, CA

FORWARD

Many conventional statistical signal processing methods treat random signals as if they were statistically stationary, in which case the parameters of the underlying physical mechanism that generates the signal would not vary with time. But for most manmade signals encountered in communication, telemetry, radar, and sonar systems, some parameters do vary periodically with time. In some cases even multiple incommensurate (not harmonically related) periodicities are involved. Examples include sinusoidal carriers in amplitude, phase, and frequency modulation systems, periodic keying of the amplitude, phase, or frequency in digital modulation systems, and periodic scanning in television, facsimile, and some radar systems. Although in some cases these periodicities can be ignored by signal processors, such as receivers which must detect the presence of signals of interest, estimate their parameters, and/or extract their messages, in many cases there can be much to gain in terms of improvements in performance of these signal processors by recognizing and exploiting underlying periodicity. This typically requires that the random signal be modeled as *cyclostationary*, in which case the statistical parameters vary in time with single or multiple periodicities. Cyclostationarity also arises in signals of natural origins, due to the presence of rhythmic, seasonal, or other cyclic behavior. Examples include time-series data encountered in meteorology, climatology, atmospheric science, oceanology, astronomy, hydrology, biomedicine, and economics. This article introduces the field of study encompassing the theory of cyclostationary signals and the exploitation of the cyclostationarity property.

This presentation is adapted from the opening plenary lecture at the Workshop on Cyclostationary Signals held August 16-18 at the Napa Valley Lodge in Yountville, California. That lecture was prepared for a mixed audience consisting of mathematical statisticians, engineers, and scientists from academia, industry, and the national government. Consequently, different parts of this presentation are addressed primarily to different segments of this general audience. However, my intention in writing this article is to have each part provide useful information for all segments. I hope it will be read in this spirit.

PLENARY LECTURE 1--PART A

Background

What is cyclostationarity?

Let us begin with the most obvious question: "What is a *cyclostationary* signal?" One answer is that a signal is cyclostationary of order n (in the wide sense) if and only if we can find some n^{th}-order homogeneous polynomial transformation of the signal that will generate finite-strength additive sine-wave components, which result in spectral lines. For example, for n = 2, a quadratic transformation (like the squared signal or the product of the signal with a delayed version of itself, or the weighted sum of such products) will generate spectral lines. For n = 3 or n = 4, cubic or quartic transformations (i.e., sums of weighted products of 3 or 4 delayed versions of the signal) will generate spectral lines. In contrast, for stationary signals, only a spectral line at frequency zero can be generated.

Another answer to this question, which is completely equivalent to the first answer but does not appear to be so upon first encounter, is that a signal is cyclostationary of order n (in the wide sense) if and only if the time fluctuations in n distinct spectral bands with center frequencies that sum to certain discrete nonzero values are statistically dependent in the sense that their joint n^{th}-order moment (the time average of their product in which each factor is shifted in frequency to have a center frequency of zero) is nonzero. In contrast, for stationary signals only those bands whose center frequencies sum to zero can exhibit statistical dependence.

In fact, for a cyclostationary signal, each distinct sum of center frequencies for which the n^{th}-order spectral moment is nonzero is identical to the frequency of a sine wave that can be generated by putting the signal through an appropriate n^{th}-order nonlinear transformation.

For the simplest nontrivial case, which is n = 2, this means that a signal x(t) is cyclostationary with *cycle frequency* a if and only if at least some of its delay-product waveforms, $y(t) = x(t - t)\, x(t)$ or $z(t) = x(t - t)\, x^*(t)$ (where $(\cdot)^*$ denotes conjugation) for some delays t, exhibit a spectral line at frequency a, and if and only if the time fluctuations in at least some pairs of spectral bands of x(t), whose two center frequencies sum (for the case of y(t)) or difference (for the case of z(t)) to a, are correlated.

If not all cycle frequencies a for which a signal is cyclostationary are multiples of a single fundamental frequency (equal to the reciprocal of a fundamental period), then the signal is said to be *polycyclostationary* (although the term cyclostationary also can be used in this more general case when the distinction is not important). This means that there is more than one statistical periodicity present in the signal.

Is cyclostationarity useful?

Perhaps the second most obvious question an engineer would ask is, "Is the property of cyclostationarity useful?" The answer is emphatically "Yes!" Cyclostationarity can generally be exploited to enhance the accuracy and reliability of information gleaned from data sets such as measurements of corrupted signals. This enhancement is relative to the accuracy and reliability of information that can be gleaned from stationary data sets or cyclostationary data sets that are treated as if they were stationary. Such information includes the following:

1) A decision as to the presence or absence of a random signal, or about the number of random signals present, with a particular modulation type in a data set also containing background noise and other modulated signals,

2) A classification of multiple received signals present in a noisy data set according to their modulation types,

3) An estimate of a signal parameter, such as a carrier phase, pulse timing, or direction of arrival, based on a noise-and-interference-corrupted data set,

4) An estimate of an analog or digital message being communicated by a signal over a channel corrupted by noise, interference, and distortion,

5) A prediction of a future value of a random signal,

6) An estimate of the input-output relation of a linear or nonlinear system based on measurements of the system's response to random excitation,

7) An estimate of the degree of causality between two data sets, and

8) An estimate of the parameters of a model for a data set.

Why have a workshop on cyclostationarity?

The next question we should consider is "Why are we having this workshop?" Some of the primary reasons are:

1) there is a growing awareness in signal processing and communications communities that the cyclostationarity inherent in many man-made random signals and some signals of natural origins (that were previously modeled as stationary) must be properly recognized and modeled if analyses of systems involving such signals are to properly reflect actual behavior;

2) there is a growing awareness of the potential for considerable enhancement of performance of signal-processing algorithms by recognizing and exploiting

cyclostationarity in the design process rather than ignoring it by treating signals as if they were stationary;

3) there is a growing awareness by theoreticians that cyclostationary processes are, in many ways, much more than a trivial variation on stationary processes and do, therefore, merit their attention to further develop and refine the theory of these processes;

4) there is a perception by engineers and scientists that cyclostationary processes are much more than a trivial variation on stationary processes and do, therefore, merit their effort to retrain—to expand their theoretical background (their analytical/conceptual "tool boxes") from stationary to cyclostationary processes; and

5) technological advances, which enable the implementation of increasingly sophisticated signal processing algorithms, have made the exploitation of cyclostationarity more viable in practice.

Why have a workshop now?

Okay. But, "Why are we having this workshop *now*?" We have important work on cyclostationary processes dating back twenty to thirty years (Bennett, 1958; Gladyshev, 1961; Brelsford, 1967; Franks, 1969; Hurd, 1969; Gardner, 1972) and the group at UC Davis has contributed for the last twenty years. Also, there have been relatively isolated contributions from many others (about two hundred authors of about three hundred papers) over the last twenty years.

Although this is true, the growth in the number of papers has recently accelerated, and it is only in the last five years that research *groups*, journal editors, and program directors at funding agencies have shown real interest. The accelerated growth in research activity is illustrated by the histogram of the number of papers on cyclostationarity published per two-year period that is shown in Figure 1.*

There does not appear to be one overriding reason for this 20- to 25-year gestation period. Rather, it evidently is a combination of the following:

1) the absence of aggressive promotion of the sort other subjects, like higher-order statistics, and time-frequency analysis and wavelets, have received;

2) the relatively late appearance of tutorial treatments:

first book-chapter	1985
first book	1987
first tutorial/survey paper	1991;

* The statistics in this graph were compiled by the author using a comprehensive bibliography that he has created over the last five years using his personal files, computerized literature searches, and the assistance of colleagues and students, most notably L. Paura, C. M. Spooner, and K. Vokurka.

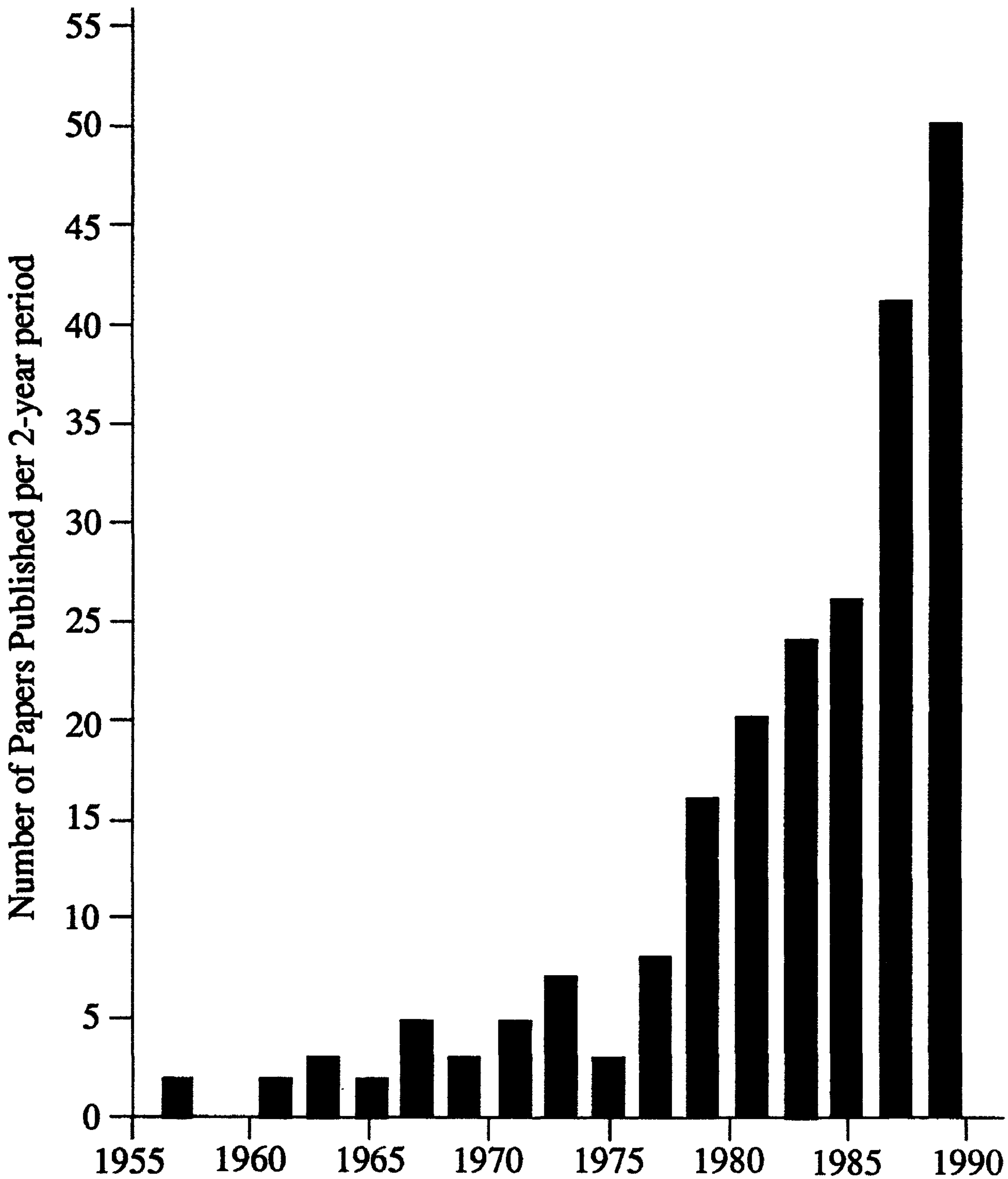


Figure 1. Histogram of Papers on Cyclostationarity

3) the widespread lack of recognition of important problems that could benefit from progress on cyclostationarity;

4) the belief by many engineers that practical advantages that *might* accrue from understanding cyclostationarity were outweighed by the required investment in retraining (exacerbated by limited university training in stochastic processes and statistical inference and decision, e.g., for digital-signal-processing designers); and

5. the long-held belief by many theoreticians that because a cyclostationary process (with *one* period) can be reinterpreted as a vector-valued stationary process (Gladyshev, 1961), there was no nontrivial work to be done in developing the theory of cyclostationary processes.

But, we are now at a turning point. Considering the following indicators, it appears that a "critical mass" of interest has been reached and, as a result, that research activity (and, I hope, progress) will undergo explosive growth:

1) acceleration in production of research papers on cyclostationarity;

2) interest of the National Science Foundation, Office of Naval Research, Army Research Office, and Air Force Office of Scientific Research in supporting this workshop;

3) interest demonstrated by the participants of this workshop;

4) recent increases in both industrial and government funding of research on cyclostationarity.

What are some of the seminal contributions to the study of cyclostationarity?

To expand our perspective on this subject, let us consider the following brief historical survey of some of the seminal contributions to the theory and application of cyclostationarity:*

(Bennett, 1958 and Franks, 1969): Establishment of cyclostationary processes as appropriate models for many communications signals

(Jacobs, 1958; Gladyshev, 1963, Gardner, 1978): First studies of cyclostationary processes with multiple periods

(Gudzenko, 1959): First study of consistency of nonparametric estimates of the Fourier coefficients of periodic autocorrelations.

---

* Contributions from the untranslated Russian literature are not included here, but it is mentioned that several Russian authors, most notably Ya. P. Dragan, have published a substantial amount on cyclostationarity.

(Gladyshev, 1961 and 1963): Discovery of equivalence between a cyclostationary process (with one period) and a vector-valued stationary process. Initial work on spectral representation.

(Brelsford, 1967): Seminal work on periodic autoregressive modeling and periodic linear prediction.

(Hurd, 1969, 1989; Gardner, 1986c, 1987a; Brown 1987): First studies of consistency of nonparametric estimates of spectral moments of cyclostationary processes with one period (Hurd) and with multiple periods (Gardner and Brown).

(Gardner, 1972; Gardner and Franks, 1975): First development and application of several series representations of cyclostationary processes in terms of jointly stationary processes for optimum periodically time-variant linear filtering of cyclostationary processes. First characterization of Fourier coefficients of periodic autocorrelations and periodic spectra (the cyclic autocorrelations and cyclic spectra) as crosscorrelations and cross-spectra of frequency-shifted versions of the process.

(Rootenberg and Ghozati, 1977, 1978; and Bittanti et al., 1987, 1992): First efforts to develop the Gauss-Markov theory of cyclostationary processes; formulation and partial solution of the cyclospectral factorization problem.

(Pagano, 1978): Development of equivalence between univariate periodic AR modeling and multivariate constant AR modeling.

(Miamee and Salehi, 1980): Extension—from stationary to cyclostationary processes—of the Wold-Cramér decomposition of a process (and its spectrum) into regular (continuous) and singular (discrete) components.

(Nedoma, 1963; Boyles and Gardner, 1983): First formulation and development of cycloergodicity for cyclostationary processes with single (Nedoma) and multiple (Boyles and Gardner) periods.

(Gardner, 1985): First *general* treatise on cyclostationary processes and their applications to signal processing and communications (1 book chapter).

(Gardner, 1986b, 1987a): First formulation and development of the nonstochastic statistical theory of cyclostationary time-series and its applications to signal processing and communications (6 book chapters).

(Gardner, 1987a; Brown, 1987; Chen, 1989; Agee, et al., 1990; Schell, 1990; Spooner, 1992): First studies of the exploitability of the separability of individual-signal contributions to cyclic temporal and spectral moments (of second order) of multiple interfering signals for the problems of detection, modulation recognition, time-delay estimation, blind-adaptive spatial filtering, and high-resolution direction finding. Discovery that spectrally overlapping signals can be separated with linear temporal processing by exploiting spectral redundancy.

(Gardner and Spooner, 1992b; Spooner and Gardner, 1992a, b; Spooner, 1992): First formulation and development of the temporal and spectral moment and cumulant theory of cyclostationary time-series.

What about terminology?

A few words about terminology are in order. The first term given to this class of processes is the term *cyclostationary* which was introduced by Bennett (1958), who also introduced the term *cycloergodic*. Other terms used include *periodically stationary*, *periodically nonstationary*, and *periodically correlated*. This last term is appropriate only for second-order (or wide-sense) cyclostationarity, whereas the preceding three terms admit the modifiers wide-sense, n^{th}-order, and strict-sense, and are, therefore, more general. The most commonly used term is *cyclostationary*.

What are some of the specific motivations for studying cyclostationarity?

There is a great deal of motivation for studying cyclostationarity. Let us consider first some of the practical motives and then some of the mathematical motives, and while we are at it, we can recognize many of the existing contributions to the study of cyclostationarity. The practical motives cited here are specified in terms of a series of facts.

<u>Fact 1</u>: Cyclostationary models, such as PAR (periodic autoregressive), PMA (periodic moving average), and PARMA (periodic autoregressive-moving average), can be more parsimonious—better fit with fewer parameters—than stationary models (AR, MA, and ARMA) are. This has been illustrated with real data from

- climatology/meteorology (Brelsford, 1967; Hasselmann, et al., 1981; Barnett, et al., 1983, 1984; Johnson et al., 1985)
- hydrology (Salas, 1972; Salas, et al., 1980; Vecchia, 1983, 1985; Thompstone, et al., 1985, Obeysekera, et al., 1986; McLeod et al., 1987; Bartolini et al., 1989)
- medicine/biology (Newton, 1982)
- oceanology (Dragan, et al., 1982, 1984, 1987)

• economics (Parzen, et al., 1979).

Fact 2: Periodic prediction of cyclostationary processes can be done (and periodic causality between cyclostationary processes can be found) when time-invariant prediction is not possible or is inferior (and time-invariant causality is not found or is weaker). Examples are given in Section II.

Fact 3: Spectrally overlapping cyclostationary signals can never be separated using time-invariant linear filters (e.g., optimum filters of the Wiener and Kalman type for stationary models of the cyclostationary signals). But they can possibly be separated using periodic filters which exploit spectral redundancy. This has been demonstrated for PAM—pulse-amplitude modulation, digital QAM—quadrature-amplitude modulation, AM—amplitude modulation, ASK—amplitude-shift-keying, and PSK—phase-shift-keying—signals (Brown, 1987; Gardner, 1987a; Gardner and Brown, 1989; Gardner and Venkataraman, 1990; Reed and Hsia, 1990; Peterson, 1992; Gardner 1992a).

Fact 4: The biases and variances of parameter estimators (e.g., for TDOA—time-difference-of-arrival, FDOA—frequency-difference-of-arrival, and AOA—angle-of-arrival—of propagating waves) can be much lower, especially for multiple interfering signals, when algorithms that exploit the signal selectivity associated with cyclostationarity (rather than ignore it by treating the signal as if it were stationary) are used. This has been demonstrated for various types of communications signals (Gardner, 1987, 1988a, 1990a; Gardner and Chen, 1988, 1992; Chen 1989; Chen and Gardner, 1992; Schell and Gardner 1989, 1990a,b,c, 1991, 1992a,b; Schell, 1990; Gardner and Spooner, 1993; Izzo, Paura, et al., 1989, 1990, 1992; Xu and Kailath, 1992)

Fact 5: For the design and analysis of systems that synchronize local digital clocks and sine-wave generators to the frequencies and phases of periodicities embedded in received communications and telemetry signals, the property of cyclostationarity is crucial (Franks, 1974, 1980; Moeneclaey, 1982, 1983, 1984; Gardner 1986a).

Fact 6: For the design of algorithms that blindly adapt sensor arrays to perform spatial filtering (for beam/null steering and/or mitigation of multipath fading effects), exploitation of signal selectivity associated with cyclostationarity has proven to be extremely powerful (Agee, Schell, and Gardner, 1987, 1988, 1990; Schell and Gardner, 1990a; Gardner 1990a) and application to multiuser wireless communications appears to be very promising (Gardner, Schell, and Murphy, 1992; Schell, Gardner, and Murphy, 1993).

Fact 7: For radio-signal analysis, including detection, classification, modulation recognition, source location, etc., the cyclic spectrum analyzer and related algorithms that exploit cyclostationarity have proven to be ideally suited (Gardner, 1985, 1986b,c, 1987a,b, 1988b,c, 1990a,c, 1991a; Brown, 1987; Roberts, 1989; Roberts, Brown, and Loomis, 1991; Brown and Loomis, 1992; Spooner and Gardner, 1991, 1992a,b; Gardner and Spooner, 1990, 1992a; Spooner, 1992).

Fact 8: For the design and analysis of communications systems that accommodate unintentional nonlinearities which inadvertently generate spectral lines from modulated message signals, the property of cyclostationarity is crucial (Campbell et al., 1983; Albuquerque et al., 1984).

Fact 9: For acoustic-noise analysis for rotating machinery, the cyclic spectrum analyzer holds promise for improved diagnosis of machine wear (e.g., in ground, air, and water vehicles, and hydroelectric plants) and for detection, classification, and location of cyclostationary noise sources (e.g., submarines) (Sherman, 1992).

Fact 10: Many statistical inference and decision problems involving multiple interfering cyclostationary signals in noise can exploit the cyclostationarity to great advantage because of the inherent noise-tolerance and separability of the cyclic features in the signals (Gardner, 1987a, 1990a, 1991a, 1992b).

Let us now consider some of the mathematical motives for studying cyclostationarity. Cyclostationary processes (including one or more periods), as a subclass of nonstationary processes, have more in common with stationary processes than do other subclasses of nonstationary processes. The common structure shared by cyclostationary processes suggests (and in some ways this has already been proven) that important theorems and special theories for stationary processes can be extended and/or generalized, and that important theorems for generally nonstationary processes can be specialized, to cyclostationary processes. This potential for mathematical progress, coupled with the increasingly recognized importance of cyclostationarity to practical problems, provides strong motivation for mathematicians to study these processes.

A few examples of important theorems/theories for stationary (or nonstationary) processes that should be—or have been—extended/generalized (or specialized) are given here (consult the key given in the footnote).

Topic 1: †† *Wiener-Khinchin and Shiryaev-Kolmogorov theorems relating temporal and spectral moments and cumulants* (Gardner 1986b, 1987a, 1990c; Gardner and Spooner, 1990; Spooner and Gardner, 1992; Spooner, 1992)

Topic 2: † *Spectral representation theory* (e.g., for harmonizable processes) (Gladyshev, 1963; Hurd, 1974, 1989b; Honda, 1982; Rao and Chang, 1988)

Topic 3: † *Wold-Cramér theorem on decomposition of a process into singular and regular components and decomposition of its spectrum into discrete and continuous components* (Miamee and Salehi, 1980)

Topic 4: ** *Wiener and Kalman smoothing, filtering, and prediction theory* (Gardner, 1972; Gardner and Franks, 1975; Gardner 1985, 1987a, 1992a; Brown, 1987; Gardner and Brown, 1989)

Topic 5: * *Theory of AR, MA, and ARMA models, linear prediction, and parametric spectral estimation* (Brelsford, 1967; Pagano, 1978; Miamee and Salehi, 1980; Tiao and Grupe, 1980; Sakai, 1982, 1983, 1990, 1991; Vecchia, 1985; Obeysekera and Salas, 1986; Li and Hui, 1988; Anderson and Vecchia, 1992)

Topic 6: * *Theory of fast algorithms for linear prediction and filtering* (Sakai, 1982, 1983)

Topic 7: * *Gauss-Markov theory* (Rootenberg and Ghozati, 1977, 1978; Bittanti, et al., 1987, 1992)

Topic 8: * *Birkhoff Ergodic Theorem and associated ergodic theory* (Nedoma, 1963; Blum and Hansen, 1966; Boyles and Gardner, 1983; Honda, 1990)

Topic 9: ** *Theory of consistent nonparametric estimation of temporal and spectral moments and cumulants* (Gudzenko, 1959; Hurd, 1969, 1989; Alekseev, 1988, 1991; Gardner, 1985, 1986c, 1987a, 1991b; Dehay, 1991; Spooner, 1992; Giannakis and Dandawate, 1991, 1992; Genossar, Lev-Ari, and Kailath, 1992; Hurd and Leskow, 1993)

---

* Some progress has been made for cyclostationary processes with *one* period.
† Substantial progress has been made for cyclostationary processes with *one* period.
** Some progress has been made for cyclostationary processes with *multiple* periods.
†† Substantial progress has been made for cyclostationary processes with *multiple* periods.

<u>Topic 10</u>: †† *Theory of higher-order statistics (temporal and spectral moments and cumulants)* (Gardner, 1990; Gardner and Spooner, 1990, 1992b; Spooner and Gardner, 1992a,b; Spooner, 1992; Giannakis and Dandawate, 1991)

REFERENCES

FOR LECTURE 1--PART A

Agee, B. G., S. V. Schell, and W. A. Gardner (1987) "Self-coherence restoral: A new approach to blind adaptation of antenna arrays," *Proceedings of the Twenty-First Annual Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, 1987, pp. 589-593.

Agee, B. G., S. V. Schell, and W. A. Gardner (1988) "The SCORE approach to blind adaptive signal extraction: an application of the theory of spectral correlation," *Proceedings of the IEEE/ASSP Fourth Workshop on Spectral Estimation and Modeling*, 3-5 August 1988, Minneapolis, MN, pp. 277-282.

Agee, B. G., S. V. Schell, and W. A. Gardner (1990) "Spectral self-coherence restoral: A new approach to blind adaptive signal extraction," *Proceedings of the IEEE*, Vol. 78, pp. 756-767.

Albuquerque, J. P. A., O. Shimbo, and L. N. Ngugen (1984) "Modulation transfer noise effects from a continuous digital carrier to FDM/FM carriers in memoryless nonlinear devices," *IEEE Transactions on Communications*, Vol. COM-32, pp. 337-353.

Alekseev, V. G. (1988) "Estimating the spectral densities of a Gaussian periodically correlated stochastic process," *Problems of Information Transmission*, Vol. 24, pp. 109-115.

Anderson, P. L., and A. V. Vecchia (1992) "Asymptotic results for periodic autoregressive moving average processes," *Journal of Time Series Analysis*, Vol. 13.

Barnett, T. P. (1983) "Interaction of the monsoon and pacific trade wind system at interannual time scales. I. The equatorial zone," *Mon. Weather Rev.*, Vol. III, pp. 756-773.

Barnett, T. P., H. D. Heinz, and K. Hasselmann (1984) "Statistical prediction of seasonal air temperature over Eurasia," *Tellus Ser. A* (Sweden), Vol. 36A, pp. 132-146.

Bartolini, P., J. D. Salas, and J. T. B. Obeysekera (1988) "Multivariate periodic ARMA (1, 1) processes," *Water Resources Research*, Vol. 24, pp. 1237-1246.

Bennett, W. R. (1958) "Statistics of regenerative digital transmission," *Bell System Tech. Jour.*, Vol. 37, pp. 1501-1542.

Bittanti, S. (1987) "The periodic prediction problem for cyclostationary processes--an introduction," *Proc. of the NATO Advanced Research Workshop*, Groningen 1986, pp. 239-249.

Bittanti, S. and G. De Nicolao (1992) "Spectral factorization of linear periodic systems with application to the optimal prediction of periodic ARMA models," *Automatica* (in press).

Blum, J. R., D. L. Hanson (1966) "On quasi-periodic probability measures," *Journal of Math. Mech.*, Vol. 15, pp. 291-303.

Boyles, R. A., and W. A. Gardner (1983) "Cycloergodic properties of discrete-parameter non-stationary stochastic processes," *IEEE Transactions on Information Theory*, Vol. IT-29, pp. 105-114.

Brelsford, W. M. (1967) "Probability predictions and time series with periodic structure," Ph.D. Dissertation, Johns Hopkins University, Baltimore, Maryland.

Brown, W. A. (1987) "On the theory of cyclostationary signals," Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, University of California, Davis, California.

Brown, W. A., and H. H. Loomis, Jr. (1992) "Digital implementation of spectral correlation analyzers," *IEEE Transactions on Signal Processing*, Vol. 40 (in press).

Campbell, J. C., A. J. Gibbs, and B. M. Smith (1983) "The cyclostationary nature of crosstalk interference from digital signals in multipair cable -- Part I: Fundamentals," *IEEE Transactions on Communications*, Vol. COM-31, pp. 629-637.

Chen, C. K. (1989) "Spectral correlation characterization of modulated signals with application to signal detection and source location," Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, University of California, Davis, California.

Chen, C. K. and W. A. Gardner (1992) "Signal-selective time-difference-of-arrival estimation for passive location of manmade signal sources in highly corruptive environments. Part II: Algorithms and performance," *IEEE Transactions on Signal Processing*, Vol. 40, No. 5, 13 pp. (in press).

Dehay, D. (1991) "Contributions to the spectral analysis of nonstationary processes," Ph.D. dissertation, Universite des Sciences et Techniques de Lille Flandres Artois, June 1991.

Dragan, Ya. P., and I. N. Yavorskii (1982) *Rhythmics of Sea Waves and Underwater Acoustic Signals*, Kiev: Naukova Dumka (Russian).

Dragan, Ya. P., V. A. Rozhkov, and I. N. Yavorskii (1984) "Applications of the theory of periodically correlated random processes to the probabilistic analysis of oceanological time series," In *Probabilistic Analysis and Modeling of Oceanological Processes* (Russian) Gardner, W. A.(V. A. Rozhkov, ed.). pp. 4-23, Leningrad: Gidrometeoizdat.

Dragan, Ya. P., V. A. Rozhkov, and I. N. Yavorskii (1987) *Methods of Probabilistic Analysis of Oceanological Rhythmics* (Russian), Leningrad: Gidrometeoizdat.

Franks, L. E. (1969) *Signal Theory*, Englewood Cliffs, N. J., Prentice-Hall.

Franks, L. E., and J. Bubrouski (1974) "Statistical properties of timing jitter in a PAM timing recovery scheme," *IEEE Transactions on Communications*, Vol. COM-22, pp. 913-930.

Franks, L. E. (1980) "Carrier and bit synchronization in data communication -- A tutorial review," *IEEE Transactions on Communications*, Vol. COM-28, pp. 1107-1121.

Gardner, W. A. (1972) "Representation and estimation of cyclostationary processes," Ph.D. Dissertation, Department of Electrical and Computer Engineering, University of Massachusetts, reprinted as *Signal and Image Processing Lab Technical Report No. SIPL-82-1*, Department of Electrical and Computer Engineering, University of California, Davis, California, 95616 (1982).

Gardner, W. A., and L. E. Franks (1975) "Characterization of cyclostationary random signal processes," *IEEE Transactions on Information Theory*, Vol. IT-21, pp. 4-14.

Gardner, W. A. (1978) "Stationarizable random processes," *IEEE Transactions on Information Theory*, Vol. IT-24, pp. 8-22.

Gardner, W. A. (1985) *Introduction to random processes with applications to signals and systems*, New York, Macmillan.

Gardner, W. A. (1986a) "The role of spectral correlation in design and performance analysis of synchronizers," *IEEE Transactions on Information Theory*, Vol. COM-34, pp. 1089-1095.

Gardner, W. A. (1986b) "The spectral correlation theory of cyclostationary time-series," *Signal Processing* (EURASIP), Vol. 11, pp. 13-36.

Gardner, W. A. (1986c) "Measurement of spectral correlation," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-34, pp. 1111-1123.

Gardner, W. A. (1987a) *Statistical Spectral Analysis: A Nonprobabilistic Theory*. Englewood Cliffs, NJ: Prentice-Hall.

Gardner, W. A. (1987b) "Spectral correlation of modulated signals, Part I -- Analog modulation," *IEEE Transactions on Communications*, Vol. COM-35, pp. 584-594.

Gardner, W. A., W. A. Brown, and C.-K. Chen (1987) "Spectral correlation of modulated signals, Part II -- Digital modulation," *IEEE Transactions on Communications*, Vol. COM-35, pp. 595-601.

Gardner, W. A. (1988a) "Simplification of MUSIC and ESPRIT by exploitation of cyclostationarity," *Proceedings of the IEEE*, Vol. 76, No. 7, pp. 845-847.

Gardner, W. A. (1988b) "Signal interception: a unifying theoretical framework for feature detection," *IEEE Transactions on Communications*, Vol. COM-36, pp. 897-906.

Gardner, W. A. (1988c) "Exploitation of spectral correlation in cyclostationary signals," *Fourth Annual ASSP Workshop on Spectrum Estimation and Modeling*, 3-5 August 1988, Minneapolis, MN, pp. 1-6.

Gardner, W. A., and C-K. Chen (1988) "Interference-tolerant time-difference-of-arrival estimation for modulated signals," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-36, pp. 1385-1395.

Gardner, W. A., and W. A. Brown (1989) "Frequency-shift filtering theory for adaptive co-channel interference removal," *Conference Record, Twenty-Third Asilomar Conference on Signals, Systems and Computers*, 30 Oct. - 1 Nov. 1989, Pacific Grove, CA, pp. 562-567.

Gardner, W. A. (1990a) *Introduction to Random Processes with Applications to Signals and Systems*, 2nd ed., New York: McGraw-Hill.

Gardner, W. A. (1990b) "Identification of systems with cyclostationary input and correlated input/output measurement noise," *IEEE Transactions on Automatic Control*, Vol. 35, pp. 449-452.

Gardner, W. A. (1990c) "Spectral characterization of n-th order cyclostationarity," *Proceedings of the Fifth IEEE/ASSP Workshop on Spectrum Estimation and Modeling*, Oct. 10-12, 1990, Rochester, NY, pp. 251-255. (Invited paper)

Gardner, W. A. and S. Venkataraman (1990) "Performance of optimum and adaptive frequency-shift filters for co-channel interference and fading," *Proceedings of the Twenty-Fourth Annual Asilomar Conference on Signals, Systems, and Computers*, Nov. 5-7, 1990, Pacific Grove, CA, pp. 242-247.

Gardner, W. A. and C. M. Spooner (1990) "Higher order cyclostationarity, cyclic cumulants, and cyclic polyspectra," *Proceedings of the 1990 International Symposium on Information Theory and Its Applications*, Nov. 27-30, 1990, Honolulu, HI, pp. 355-358.

Gardner, W. A. (1991a) "Exploitation of spectral redundancy in cyclostationary signals," *IEEE Signal Processing Magazine*, Vol. 8, pp. 14-36.

Gardner, W. A. (1991b) "Two alternative philosophies for estimation of the parameters of time-series," *IEEE Transactions on Information Theory*, Vol. 37, pp. 216-218.

Gardner, W. A., and W. A. Brown (1991) "Fraction-of-time probability for time-series that exhibit cyclostationarity," *Signal Processing*, Vol. 23, No. 3, pp. 273-292.

Gardner, W. A. (1992a) "Cyclic Wiener filtering: Theory and method," *IEEE Transactions on Communications*, Vol. 40, December 1992, (in press).

Gardner, W. A. (1992b) "A unifying view of coherence in signal processing," *Signal Processing* (EURASIP), Vol. 23.

Gardner, W. A., and Chen, C. K. (1992), "Signal-selective time-difference-of-arrival estimation for passive location of manmade signal sources in highly corruptive environments. Part I: Theory and method," *IEEE Transactions on Signal Processing*, Vol. 40, No. 1, 18 pp. (in press).

Gardner, W. A., S. V. Schell, and P. Murphy, (1992) "Multiplication of cellular radio capacity by blind adaptive spatial filtering," accepted for publication in *1992 International Conference on Selected Topics in Wireless Communications*, June 25-26 and *Proceedings of the 22nd Annual IEEE Communication Theory Workshop*, June 28-July 21, 1992, 5 pp.

Gardner, W. A., and C. M. Spooner, (1992a) "Signal interception: Performance advantages of cyclic feature detectors," *IEEE Transactions on Communications*, Vol. 40, No. 1, pp. 149-159.

Gardner, W. A., and C. M. Spooner (1992b) "The cumulant theory of cyclostationary time-series, Part I: Foundation," *Technical Report*, March 1992, Department of Electrical and Computer Engineering, University of California, Davis.

Gardner, W. A., and T. L. Archer (1993) "Exploitation of cyclostationarity for identifying the Volterra kernels of nonlinear systems," *IEEE Transactions on Information Theory*, Vol. 39.

Gardner, W. A., and L. Paura (1993) "Identification of polyperiodic nonlinear systems," *IEEE Transactions on Information Theory*, Vol. 39.

Gardner, W. A. and C. M. Spooner (1993) "Detection and source location of weak cyclostationary signals: Simplifications of the maximum-likelihood receiver," *IEEE Transactions on Communications*, 1993 (in press).

Genossar, M. J., H. Lev-Ari, and T. Kailath, (1993) "Estimating cyclic autocorrelation," *IEEE Transactions on Signal Processing*, Vol. 41 (in press).

Giannakis, G. B., and A. B. Dandawate (1991) "Poly spectral analysis of (almost) cyclostationary signals: LPTV system identification and related applications," *Proceedings of the International Workshop on Higher-Order Statistics,* Chamrousse, France, July 1991, pp. 147-150.

Gladyshev, E. G. (1961) "Periodically correlated random sequences," *Soviet Math. Dokl.*, Vol. 2, pp. 385-388.

Gladyshev, E. G. (1963) "Periodically and almost periodically correlated random processes with continuous time parameter," *Theory Prob. Appl.* Vol. 8, pp. 173-177.

Gudzenko, L. I. (1959) "On periodic nonstationary processes," *Radio Eng. Electron. Phys.* (Russian), Vol. 4, pp. 220-224.

Hasselmann, K., and T. P. Barnett (1981) "Techniques of linear prediction for systems with periodic statistics," *Journal of Atmospheric Science*, Vol. 38, pp. 2275-2283.

Honda, I. (1982) "On the spectral representation and related properties of periodically correlated stochastic process," *The Transactions of the IECE of Japan*, Vol. E65, pp. 723-729.

Honda, I. (1990) "On the ergodicity of Gaussian periodically correlated stochastic processes," *Transactions of the Institute of Electronics, Information and Communication Engineers E*, Vol. E73, pp. 1729-1737.

Hurd, H. L. (1969) "An investigation of periodically correlated stochastic processes," Ph.D. Dissertation, Duke University, Durham, North Carolina.

Hurd, H. L. (1974) "Stationarizing properties of random shifts," *SIAM Journal of Applied Math.*, Voi. 26, pp. 203-212.

Hurd, H. L. (1989a) "Nonparametric time series analysis for periodically correlated processes," *IEEE Transactions on Information Theory*, March 1989, Vol. 35, pp. 350-359.

Hurd, H. L. (1989b) "Representation of strongly harmonizable periodically correlated processes and their covariances," *Jour. of Multivariate Anal.*, Vol. 29, pp. 53-67.

Hurd, H. L. (1991) "Correlation theory of almost periodically correlated processes," *Jour. Multivariate Anal.*, Vol. 37, No. 1, pp. 24-45.

Hurd, H. L., and J. Leskow (1992) "Estimation of the Fourier coefficient functions and their spectral densities for Φ-mixing almost periodically correlated processes," *Statistics and Probability Letters*. (in press)

Hurd, H. L., and N. L. Gerr (1991) "Graphical methods for determining the presence of periodic correlation," *Journal of Time Series Analysis*. (in press)

Izzo, L., L. Paura, and G. Poggi (1989) "Multiple-source localization: a new method exploiting the cyclostationarity property," *Proceedings of Douzième Colloque sur le Traitement du Signal et des Images*, Juan-les-Pins, France, pp. 481-484.

Izzo, L., A. Napolitano, L. Paura (1990) "Interference-tolerant estimation of amplitude and time-delay parameters of a composite signal," *Proceedings of Fifth European Signal Processing Conference* (EUSIPCO '90), Barcelona, 18-21 September 1990, pp. 103-106.

Izzo, L., L. Paura, and M. Tanda (1992) "Signal interception in non-Gaussian noise," *IEEE Transactions on Communications* Vol. 40, pp. 1030-1037, June 1992.

Izzo, L., L. Paura, and G. Poggi (1992) "An interference-tolerant algorithm for localization of cyclostationary-signal sources," *IEEE Transactions on Signal Processing* Vol. 40, pp. 1682-1686, July 1992.

Jacobs, K. (1958) "Almost periodic Markov processes," *Mathematics Annual,* Vol. 134, pp. 408-427 (German).

Johnson, C. M., P. Lemke, and T. P. Barnett (1985) "Linear prediction of sea ice anomalies," *Journal of Geophys. Res.*, Vol. 90, pp. 5665-5675.

Li, W. K., and Y. V. Hui (1988) "An algorithm for the exact likelihood of periodic autoregressive moving average models," *Comm. Stat., Simulation Comput.*, Vol. 17, pp. 1483-1494.

McLeod, A. I., D. J. Noakes, K. W. Hipel, and R. M. Thompstone (1987) "Combining hydrologic forecasts," *Journal of Water Resources Planning and Management,* Vol. 113, pp. 29-41, January 1987.

Miamee, A. G., and H. Salehi (1980) "On the prediction of periodically correlated stochastic processes," *Multivariate Analysis-V*, P. R. Krishnaiah (ed.), Amsterdam, North Holland Publishing Company, pp. 167-179.

Moeneclaey, M. (1982) "Linear phase-locked loop theory for cyclostationary input disturbances," *IEEE Transactions on Communications*, Vol. COM-30, pp. 2253-2259.

Moeneclaey, M. (1983) "The optimum closed-loop transfer function of a phase-locked loop used for synchronization purposes," *IEEE Transactions on Communications*, Vol. COM-31, pp. 549-553.

Moeneclaey, M. (1984) "A fundamental lower bound on the performance of practical joint carrier and bit synchronizers," *IEEE Transactions on Communications*, Vol. COM-32, pp. 1007-1012.

Nedoma, J. (1963) "Über die ergodizität and r-ergodizität stationärer wahrscheinlichkeitsmasse," *Z. Wahrscheinlichkeitstheorie*, Vol. 2, pp. 90-97.

Newton, H. J. (1982) "Using periodic autoregressions for multiple spectral estimation," *Technometrics*, Vol. 24, pp. 109-116.

Obeysekera, J. T. B., and J. D. Salas (1986) "Modeling of aggregated hydrologic time series," *Journal of Hydrol.* Vol. 86, pp. 197-219.

Pagano, M. (1978) "On periodic and multiple autoregressions," *Ann. Statist.*, Vol. 6, pp. 1310-1317.

Parzen, E., and M. Pagano (1979) "An approach to modeling seasonally stationary time–series," *Journal of Econometrics*, Vol. 9, North Holland Publishing Company, pp. 137-153.

Petersen, B. R. (1992) "Equalization in Cyclostationary Interference," Ph.D. Dissertation, Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada.

Pourahmadi, M., and H. Salehi (1983) "On subordination and linear transformation of harmonizable and periodically correlated processes," *Probability Theory on Vector Spaces, III* (Lublin), Berlin-New York: Springer, pp. 195-213.

Rao, M. M., D. K. Chang (1988) "Special representations of weakly harmonizable processes," *Stochastic Analysis and Applications,* Vol. 6, pp. 169-190.

Reed, J. H., and T. C. Hsia (1990) "The performance of time-dependent adaptive filters for interference rejection," *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol. 38, pp. 1373-1385.

Roberts, R. S. (1989) "Architectures for digital cyclic spectral analysis," Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, University of California, Davis, California.

Roberts, R. S., W. A. Brown, and H. H. Loomis, Jr. (1991) "Computationally efficient algorithms for cyclic spectral analysis," *IEEE Signal Processing Magazine*, Vol. 8, pp. 38-49.

Rootenberg, J., and S. A. Ghozati (1978) "Generation of a class of nonstationary random processes, "*International Journal of Systems and Science*, Vol. 9, pp. 935-947.

Rootenberg, J., and S. A. Ghozati (1977) "Stability properties of periodic filters," *International Journal of Systems and Science*, Vol. 8, pp. 953-959.

Sakai, H. (1982) "Circular lattice filtering using Pagano's method," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-30, pp. 279-287.

Sakai, H. (1983) "Covariance matrices characterization by a set of scalar partial autocorrelation coefficients," *The Annals of Statistics*, Vol. 11, pp. 337-340.

Sakai, H. (1990) "Spectral analysis and lattice filter for periodic autoregressive processes," *Electronics and Communications in Japan, Part 3*, January 1990, Vol. 73, pp. 9-15.

Sakai, H. (1991) "On the spectral density matrix of a periodic ARMA process," *Journal of Time Series Analysis*, Vol. 12, pp. 73-82.

Salas, J. D., (1972) "Range analysis for storage problems of periodic stochastic processes," Ph.D. dissertation, Department of Civil Engineering, Colorado State University, Fort Collings, CO.

Salas, J. D., R. A. Smith (1980) "Correlation properties of periodic AR(r) models," *Proceedings of the 3rd International Symposium on Stochastic Hydraulics*, August 5-7, 1980, Tokyo, pp. 107-115.

Schell, S. V., and B. G. Agee (1988) "Application of the SCORE algorithm and SCORE extensions to sorting in the rank-L spectral self-coherence environment," *Conference Record, Twenty-Second Asilomar Conference on Signals, Systems and Computers*, 31 Oct. - 2 Nov. 1988, Pacific Grove, CA, Vol. 1, pp. 274-278.

Schell, S. V., R. A. Calabretta, W. A. Gardner, and B. G. Agee (1989) "Cyclic MUSIC algorithms for signal-selective direction estimation," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, Glasgow, May 23-26, 1989, pp. 2278-2281.

Schell, S.V., and W. A. Gardner (1989) "Signal-selective direction finding for fully correlated signals," *Abstracts of Sixth Multidimensional Signal Processing Workshop of the IEEE/ASSP Society*, 6-8 Sept., 1989, Pacific Grove, CA, pp. 139-140.

Schell, S. V. (1990) "Exploitation of spectral correlation for signal-selective direction finding," Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, University of California, Davis, California.

Schell, S. V., and W. A. Gardner (1990a) "Signal-selective high-resolution direction finding in multipath," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, Albuquerque, NM, April 3-6, 1990, pp. 2667-2670.

Schell, S. V., and W. A. Gardner (1990b) "Progress on signal-selective direction finding," *Proceedings of the Fifth IEEE/ASSP Workshop on Spectrum Estimation and Modeling*, Oct. 10-12, 1990, Rochester, NY, pp. 144-148.

Schell, S. V., and W. A. Gardner (1990c) "Detection of the number of cyclostationary signals in unknown interference and noise," *Proceedings of the Twenty-Fourth Annual Asilomar Conference on Signals, Systems, and Computers*, Nov. 5-6, 1990, Pacific Grove, CA, pp. 473-477.

Schell, S. V. and W. A. Gardner (1991) "Estimating the directions of arrival of cyclostationary signals—Part I: Theory and methods," Technical Report, November 1991, Department of Electrical and Computer Engineering, University of California, Davis.

Schell, S. V. and W. A. Gardner (1992a) "High resolution direction finding," Chapter in *Handbook of Statistics*, N. K. Bose and C. R. Rao (Eds.), Amsterdam: Elsevier.

Schell, S. V. and W. A. Gardner (1992b) "Cramer-Rao lower bound for parameters of Gaussian cyclostationary signals," *IEEE Transactions on Information Theory*, Vol. 38, pp. 1418-1422, July 1992.

Schell, S. V., and W. A. Gardner (1993) "Blind adaptive spatio-temporal filtering for wideband cyclostationary signals," *IEEE Transactions on Signal Processing*, Vol. 41.

Schetzen, M. (1989) *The Volterra and Wiener Theories of Nonlinear Systems*, Second Edition, Malabar, Florida: Krieger Publ. Co.

Sherman, P. J. (1992) "Random processes from rotating machinery," *Proceedings of the Workshop on Nonstationary Stochastic Processes and Their Applications,* Hampton, VA, August 1-2, 1991, Singapore: World Scientific.

Spooner, C. M., and W. A. Gardner (1991) "Estimation of cyclic polyspectra," *Proceedings of Twenty-fifth Annual Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, Nov. 4-6, 1991.

Spooner, C. M., and W. A. Gardner (1992a) "An overview of higher-order cyclostationarity," *Proceedings of NASA Langley/Hampton University Workshop on Nonstationary Stochastic Processes and Their Applications*, Hampton, VA, Aug. 1-2, 1991.

Spooner, C. M., and W. A. Gardner (1992b) "The cumulant theory of cyclostationary time-series, Part II: Development and applications," Technical Report, March 1992, Department of Electrical and Computer Engineering, University of California, Davis.

Spooner, C. M., (1992) "Theory and application of higher-order cyclostationarity," Ph.D. dissertation, Department of Electrical and Computer Engineering, University of California, Davis.

Thompstone, R. M., ,. W. Hipel, and A. I. McLeod (1985) "Grouping of periodic autoregressive models," *Time Series Analysis: Theory and Practice 6*, edited by O. D. Anderson, J. K. Ord, and E. A. Robinson, pp. 35-49, Amsterdam: (Elsevier, North-Holland).

Tiao, G. C., and M. R. Grupe (1980) "Hidden periodic autoregressive-moving average models in time series data," *Biometrika*, Vol. 67, pp. 365-373.

Vecchia, A. V. (1985) "Maximum likelihood estimation for periodic autoregressive Moving Average Models," *Technometrics*, Vol. 27, pp. 375-384.

Wold, H. O. A. (1948) "On prediction in stationary time-series," *Ann. Math. Stat.*, Vol. 19, pp. 558-567.

Xu, G., and T. Kailath (1992) "Direction-of-arrival estimation via exploitation of cyclostationarity--A combination of temporal and spatial processing," *IEEE Transactions on Signal Processing,* Vol. 40, pp. 1775-1786.

Zivanovic, G. D., and W. A. Gardner (1991) "Degrees of cyclostationarity and their application to signal detection and estimation," *Signal Processing* (EURASIP), Vol. 22, pp. 287-297.

PLENARY LECTURE 1--PART B

Stochastic and Nonstochastic Modeling of Cyclostationary Signals

In this lecture, two alternative conceptual/theoretical frameworks for studying cyclostationary signals are compared and contrasted: the framework of stochastic processes and the framework of nonstochastic time-series. Within each framework, the properties of pure and impure stationarity, cyclostationarity, and polycyclostationarity are defined, and the duality between the two frameworks is explained in terms of the central operation within each framework: the expectation operation for stochastic processes and the polyperiodic component extractor, which can be interpreted as a temporal expectation operation, for time-series. The properties of cycloergodicity and polycycloergodicity are defined, and the complication of hidden cyclostationarity that results from stochastic process models that lack certain (poly) cycloergodic properties is explained, and its ramifications are illustrated with a variety of examples. Technical problem areas, within each framework, where mathematical progress is needed are delineated. The lecture closes with a recommendation to engineers and scientists to adopt the theoretical framework of nonstochastic time-series wherever it is applicable because it avoids unnecessary abstractions that widen the gap between theory and practice.

Introduction to the Theory and Application of Wide-Sense Cyclostationarity

In this lecture the principles of cyclostationarity that are directly useful in the design and analysis of signal processing algorithms and the development of new system concepts are introduced. The focus is on wide-sense cyclostationarity (and polycyclostationarity) which concerns sine-wave components in lag-product waveforms, whose Fourier coefficients are the limit cyclic autocorrelations of the signal, and their frequency-domain interpretations in terms of temporal correlation between fluctuations in separate spectral bands of the cyclostationary signal. The basic block diagram of a spectral correlation analyzer is presented and two digital implementations are described: one for the basic method that time-averages products of frequency samples and the other for the derivative of this method which uses frequency-smoothing of these products. The relationship between the temporal/spectral resolution product and reliability of the spectral correlation measurement is explained. The idealized limit of the practical measurement of spectral correlation is introduced and the cyclic Wiener relation, which establishes that this limit spectral correlation function is the Fourier transform of the limit cyclic autocorrelation, is discussed. The equivalence between these two limit functions and the cross spectrum and crosscorrelation, respectively, of frequency-shifted versions of the signal is described and the normalizations that convert the two limit functions into correlation coefficients in the frequency and time domains are specified. The effects of signal processing operations, including filtering, signal multiplication, time-sampling, and frequency down-conversion, on the spectral correlation function are described analytically and graphically. Applications to various signal processing problems in which cyclostationarity can be used to considerable advantage are described. These include detection, modulation recognition, source location, and waveform extraction for signals that are severely corrupted by noise and interference.

PLENARY LECTURE 2

POLYPERIODIC LINEAR FILTERING

L. E. Franks
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA

This summarizes a tutorial lecture on the properties and basic theory of periodically- and polyperiodically-time-varying linear systems. As such, the lecture is intended to complement the presentations on cyclostationary signals, which constitute the main thrust of the workshop. Time-varying systems are extensively employed as signal extraction and parameter estimation filters for such signals as well as models for the generation of cyclostationary processes. We consider various forms of input/output and state-variable descriptions of the systems and the nature of the implementation configurations suggested by these descriptions. Inasmuch as periodicity is a certain form of constancy, or persistence, in time, we expect to see more similarities with time-invariant systems than would be exhibited by time-varying systems in general. We show that all the system descriptions lead to implementation configurations having an embedded time-invariant component. The periodically-varying component consists solely of zero-memory operations; i.e., multiplications by periodic waveforms on an instantaneous basis. We refer to the devices for performing these multiplications as modulators. From a historical perspective, the earlier work in electrical periodically-varying systems dealt primarily with circuits such as the parametric amplifier, which contained reactive elements, such as a capacitor, which were "pumped" by a local oscillator. Thus the prevailing view of the configuration of such systems was that of a few variable-parameter elements located at various points within a predominantly time-invariant system. The practical utility of such devices inspired a great deal of research into the basic properties of periodically-time-varying linear systems, leading to canonical realizations which today form the basis for design of signal processors having the desired signal transformation characteristics.

Our primary focus is on the properties of the impulse response function of the periodically time varying (PTV) system. The impulse response, h(t,s), of a PTV system satisfies a periodicity condition of the form: $h(t+T,s+T) = h(t,s)$ for some period parameter T and all t and s. This condition permits a Fourier series expansion of the form:

$$h(t,s) = \sum_{k=-\infty}^{\infty} p_k(t-s)\, e^{j2\pi kt/T} \qquad (1)$$

The "Fourier coefficients," $p_k(t-s)$, are the impulse responses of a set of time-invariant subsystems which, combined in a parallel fashion with an output modulator, of frequency k/T, in each path, forms the complete PTV system configuration. Alternate configurations can be derived by applying simple path equivalences.

An important generalization of the PTV system is the polyperiodic linear system wherein the restriction that the exponential functions in (1) all have harmonically-related frequencies is removed. If the set of frequencies, $\{k/T \;;\; k \text{ integer}\}$, for the PTV system is replaced by an arbitrary discrete set, $\left\{f_k\right\}$, then (1) can be regarded as the expansion of an almost-periodic function. A common situation where the polyperiodic filter response is required arises in the extraction of a bandpass carrier signal at frequency f_0 carrying a baseband synchronous digital data signal with a symbol rate of $1/T$. Such a signal is most naturally regarded as polycyclostationary since there is usually no practical reason to regard f_0 and $1/T$ as harmonically related; they could possibly be incommensurate numbers. The capability of (1) to characterize both PTV and polyperiodic systems is one of its main advantages.

Another useful application for the Fourier-series type representation is in the analysis of PTV systems that are designed to implement a time-invariant (convolution) signal processing operation. This approach is used because of the unique implementation advantages that can result. Important examples are analog integrated-circuit switched capacitor filters, the N-path filter for realization of multiple passband (comb) filters, and digital filters using PTV subsystems to eliminate expensive multiplier circuitry. We discuss some of these applications and show how suitable input and output bandlimiting will make the overall PTV system equivalent to a time-invariant system.

The implementation configuration implied by (1) is not physically realizable unless the Fourier series expansion can be replaced by a finite sum, or unless suitable bandwidth constraints can be placed upon the input and output signals. Even considering a finite series, a measure of harmonic complexity; e.g., some form of period-bandwidth product parameter, is not necessarily a meaningful measure of implementation costs. For most purposes, the order of the differential equation describing the system dynamics is a more accurate indication of implementation complexity. It is certainly more closely related to the number of components in the time-invariant subsystem of the overall PTV filter. For a digital system, the system order is a direct indication of memory requirements for the processor.

We consider the general M^{th} order time-varying system in terms of its state-variable representation and examine some of the properties of the state transition matrix. Then for the case of periodic time variation, we show that the transition matrix has the special form of the product of a periodic, non-singular M x M matrix and an exponential matrix typical of a time-invariant system. With the aid of a series of linear transformations on the state vector, we arrive at a system description that has substantial implementation advantages. At this stage the impulse response of the PTV system has the finite, separable form:

$$h(t,s) = \sum_{i=1}^{M} c_i(t) e^{\lambda_i (t-s)} b_i(s) \quad ; \quad t \geq s \tag{2}$$

This implies an implementation configuration consisting of M parallel (uncoupled) paths. Each path has an input modulator, $b_i(t)$, (not necessarily exponential), an output modulator, $c_i(t)$, flanking a first-order, time-invariant filter with a pole at λ_i. Even for a complex conjugate pole pair, we are able to avoid the usual cross-coupled second-order system. We show an equivalent subsystem with two parallel paths realizing the real part of the pole position, along with an input and output configuration of sinusoidal modulators which produce an arbitrary imaginary part for the pole position.

The second part of the lecture concerns application of optimum periodic and polyperiodic filtering to problems of extracting a cyclostationary signal from additive noise or other types of signal interference. As a preliminary to the discussion, we review the Harmonic Series Representation (HSR) scheme for representing an arbitrary signal in terms of a sequence of bandlimited signals. The HSR is particularly appropriate for a wide-sense cyclostationary process because the sequence of bandlimited representor processes is jointly wide-sense stationary. Thus when the HSR is used in conjunction with the orthogonality principle for minimum mean-squared-error continuous waveform estimation, the implicit expression for the optimum filter is a frequency-domain matrix equation bearing a strong resemblance to the optimum (Wiener) filter for the analogous stationary filtering problem.

We illustrate the foregoing result with a problem from the field of spread-spectrum communications. Suppose that a stationary message signal, x(t), is multiplied by an arbitrary periodic spreading signal, c(t). The resulting signal is transmitted over an additive white-noise channel. The receiver filter is required to transform the received signal, z(t) = c(t)x(t) + n(t), into a minimum mean-squared-error estimate of x(t). We view this as a problem of extracting the signal from additive noise and self interference due to spectral overlap of frequency-shifted versions of x(t) created by the modulation process with c(t). Assuming that x(t) is bandlimited and that the period of c(t) is short enough so that the frequency-domain spacing of its harmonics is sufficiently great, then there will be no spectral overlap. We consider this case first and show that the optimum filter is simply multiplication by c(t) followed by a lowpass filter. Next we consider the case where the period of c(t) is increased to the extent that there is spectral overlap with only adjacent frequency-shifted versions of x(t). The solution is a multiplication by c(t) followed by a PTV filter with three parallel paths. The m.s. error is shown to go to zero as the additive noise vanishes, indicating that the optimum PTV filter is capable of completely eliminating the interference due to spectral overlap.

As a second example of a waveform extraction or recovery problem, we consider the problem of linear demodulation of a bandpass carrier signal when one or more interfering signals are present with significant spectral overlap with the signal of interest, as well as additive noise. The received signal is most properly modeled as a polycyclostationary process since the various cycle frequencies of the process, i.e., the various carrier frequencies and baseband baud rates and combinations thereof, are not necessarily harmonically related. Another aspect of this problem that needs to be addressed arises from the traditional usage of a complex envelope to represent carrier-type signals. Unlike the case of time-invariant bandpass filtering where there is an equivalent lowpass filtering operation on the complex envelope, a more general linear bandpass operation may correspond to an additive combination of linear filtering on the complex signal and its conjugate. This is referred to as linear/conjugate-linear (LCL) filtering. We present results from a study of the performance of constrained-optimum LCL filtering in a variety of interference situations. The constrained optimum refers to the fact that the minimum error is obtained for a receiver filter using a fixed number of frequency shifts. As the number of allowed frequency-shift and filter operations is increased, the performance is asymptotically limited by the additive noise level, indicating that interference from other carrier signals can be completely eliminated.

PLENARY LECTURE 3

AN OVERVIEW OF SENSOR ARRAY PROCESSING FOR CYCLOSTATIONARY SIGNALS

Stephan V. Schell
Department of Electrical and Computer Engineering
The Pennsylvania State University
University Park, PA

The three primary goals of the overview presented in this lecture are the following: (1) to describe in a brief but tutorial manner the state of the art of processing cyclostationary signals with sensor arrays and the performance of the current methods, (2) to show how the understanding of these methods can be used in the design of communication systems to increase capacity and/or improve signal quality relative to existing systems, and (3) to describe several open research problems in sensor array processing for cyclostationary signals. Whereas the first is intended to speed the self-education of colleagues who are knowledgeable about cyclostationary signals or sensor array processing but not necessarily both, the last is intended to speed the involvement of colleagues who are already knowledgeable about both but are simply interested in another perspective and additional ideas on important and challenging research problems. The middle goal provides one possible bridge between the first and last goals by demonstrating the advantages of understanding sensor array processing for cyclostationary signals, by identifying problems to be solved in the communication system design presented here, and by pointing out that the role of cyclostationarity-exploiting methods in the design of communication systems is itself an open problem.

Arrays of sensors such as radio antennas are useful in the process of detecting the presence of propagating signals, estimating their directions of arrival and other parameters, and estimating the signal waveforms themselves. Application areas include radar, sonar, commercial communications monitoring, signals intelligence, biomedical signal processing, geophysical exploration, communication systems, and others. However, in some of these applications the prior knowledge required by conventional methods for performing these tasks is difficult, costly, or simply impossible to obtain. Furthermore, conventional methods that are derived for sine waves or stationary Gaussian noise cannot exploit many of the statistical properties of structured manmade signals, especially those used in communication systems.

Fortunately, almost all manmade communication signals exhibit a statistical property called *cyclostationarity* which can be exploited to favor desired signals and to discriminate against undesired signals, interference, and noise in various signal processing tasks without requiring troublesome prior knowledge. In particular, methods of direction estimation and adaptive spatial filtering that exploit cyclostationarity require only knowledge of the baud rate, carrier frequency, or other frequency that characterizes the underlying periodicity exhibited by the desired signals. It is explained in this overview how this knowledge is used to avoid the need for training signals, estimates of directions of arrival, and array calibration data in spatial filtering schemes, and to avoid the need for knowledge of noise characteristics and soften the strict requirements on the number and angular spacing of signals in directing finding schemes.

An application of this understanding to the design of a cellular communication system is then presented. The continuing boom in demand for telecommunications exceeds current capacity in some markets and is expected to increase sharply as more bandwidth-intensive commercial services such as multimedia-based conferencing, information retrieval, and electronic banking and shopping are introduced. In this overview it is shown how understanding of sensor array processing methods for cyclostationary signals can be used in the design of a scheme that substantially increases capacity relative to existing systems.

Throughout the overview open problems are identified. These problems range from highly applied, such as efficient implementation of these signal processing methods and design of communication systems, to relatively theoretical, such as statistically optimum detection and estimation of cyclostationary signals and analytical performance prediction.

PLENARY LECTURE 4

HIGHER-ORDER STATISTICS FOR NONLINEAR PROCESSING OF CYCLOSTATIONARY SIGNALS

Chad M. Spooner
Department of Electrical and Computer Engineering
University of California
Davis, CA

This lecture presents a tutorial treatment of the higher-order statistics of cyclostationary signals, their properties, and their application to communication-signal processing. The theory of the higher-order statistics of cyclostationary signals is called higher-order cyclostationarity to distinguish it from the theory of the higher-order statistics of stationary signals, which is commonly called simply higher-order statistics. The difference between the two is that the higher-order statistics of cyclostationary signals, for example *n*th-order moments and cumulants, are periodic or polyperiodic in the time-translation parameter, whereas the higher-order statistics of stationary signals are constant with respect to the time-translation parameter. This difference implies that the higher-order statistics of a cyclostationary signal must be treated differently from those for a stationary signal; a new theory is needed to handle the periodicities.

The practical motivation for studying the higher-order statistics of cyclostationary signals is provided by describing several signal processing tasks that are difficult or impossible to accomplish by using either the ordinary second-order statistics (the power spectral density and autocorrelation function) or by using the less familiar second-order cyclic statistics (the cyclic spectral density and cyclic autocorrelation). It is important to note that cyclostationary signals are commonly encountered in signal processing problems since virtually every manmade signal is cyclostationary. Some examples are analog amplitude and frequency modulation and digital quadrature-amplitude modulation (QAM), which includes pulse-amplitude modulation, amplitude-shift keying, and phase-shift keying as special cases.

Because the lecture is tutorial in nature, emphasis is placed on explicitly showing the connections between the new parameters and other parameters that may be familiar to the audience. Specifically, the higher-order statistics of cyclostationary signals are shown to reduce to: (i) the higher-order statistics of stationary signals when the signal is assumed to be stationary, (ii) the second-order statistics of cyclostationary signals when the order is set equal to two and, (iii) the power spectrum and autocorrelation when the signal is assumed to be stationary and the order is set equal to two. Similarly, the relations between temporal and spectral moments and cumulants of cyclostationary signals are shown to reduce--in certain special cases--to the relationships between the temporal cumulant and polyspectrum for stationary signals, the cyclic autocorrelation and cyclic spectral density for cyclostationary signals and order equal to two (the cyclic Wiener relation), and the well-known relation between the autocorrelation and power spectral density for stationary signals and order equal to two (the Wiener-Khinchin relation).

The lecture demonstrates the general benefits of using the second-order cyclic statistics, namely signal-selectivity, and of higher-order statistics of stationary signals, namely tolerance to Gaussian corruption and preservation of phase information (for example, timing parameters can be estimated from these statistics), and shows that the higher-order cumulants--but not moments--of cyclostationary signals combine these benefits. Because some in the audience may not be familiar with cumulants, and because they are central to the theory of higher-order cyclostationarity, an introduction to cumulants is provided.

It is shown that the Fourier coefficients of the polyperiodic higher-order temporal cumulants of cyclostationary signals--called cyclic cumulants--can be given a powerful interpretation in terms of sine-wave generation. This is done by first interpreting the Fourier coefficients of the polyperiodic temporal moment function as the strengths of sine waves that are contained in higher-order lag products of the signal, and then attempting to purify these moment sine-wave strengths. The aim of this purification process is to remove the contributions of sine waves corresponding to lower-order factors in the lag product from the temporal moment function coefficients. Only those lower-order sine-wave strengths that correspond to frequencies that sum to the frequency of the temporal-moment-function Fourier coefficient need to be subtracted. These purified moment sine-wave strengths are shown to be exactly equivalent to the Fourier coefficients of the polyperiodic temporal cumulant function, and the corresponding sine waves are called pure sine waves. Thus, cumulants can be thought of as the amount of extra information contained in the nth-order moment that is not in the lower-order moments, which is an interpretation that has obvious engineering importance.

The higher-order moments and cumulants of simple signals such as sine waves and impulse trains are computed, and the effects of signal processing operations on higher-order moments and cumulants are determined. The operations include product modulation by a (poly)periodic waveform (such as a sine wave or square wave), linear time-invariant filtering (convolution), and signal addition. As an example of the use of these relations for an important signal class, the higher-order moments and cumulants for digital QAM signals are computed by representing such signals as a series of relatively simple operations on a discrete-time stationary message signal. The resulting formulas are numerically evaluated and graphs are provided to illustrate their behavior.

Estimators for all of the temporal and spectral moments and cumulants are presented, and their complexity is derived and computed for several representative cases of interest. Measurements of temporal moments and cumulants and spectral cumulants for digital QAM signals are presented and compared to the corresponding ideal functions. For the purpose of illustrating the property of signal selectivity, measurements of cyclic cumulants are made for the case of a signal of interest that is corrupted by interfering cyclostationary signals, and they are compared to measurements of higher-order statistics for the same data, that is, measurements corresponding to the case in which the signals are treated as if they were stationary.

Applications of the theory to the problems of weak-signal detection and interference-tolerant time-delay estimation are considered. The detection problem is partitioned into three subproblems: (i) the general search problem, in which there is no *a priori* information about the received data, and in which the goal is to detect any and all cyclostationary signals that may be present, (ii) the known-cycle-frequency problem, in which only the frequency of a Fourier coefficient of an nth-order cumulant is known and, (iii) the known-modulation problem in which all the moments and cumulants of a signal of interest are known. Least-squares cumulant matching is used to construct a class of time-delay estimators. The basis of the approach is that an estimate of the cyclic cumulant of the received data approaches the cyclic cumulant of only the signal of interest as the data collection length increases because of the property of signal selectivity. It is shown that two of the estimators in the class correspond to higher-order generalizations of second-order cyclic time-delay estimators that have been previously studied.

A major theme of the lecture is that higher-order cyclostationarity is best developed within the nonstochastic framework of infinite-time averages--the fraction-of-time probabilistic framework--rather than the stochastic process framework because it renders the resulting theory, concepts, and methods more accessible to the practicing engineer.

LIKELIHOOD RATIO DETECTION OF CYCLOSTATIONARY GAUSSIAN SIGNALS IN STATIONARY GAUSSIAN NOISE

John W. Betz
The MITRE Corporation
Bedford, MA

Detection of cyclostationary signals in stationary Gaussian noise has been considered in several contexts. Exact likelihood ratio detectors for keyed signals with unknown signal parameters have been derived [3]. Quadratic detectors of weak cyclostationary signals have also been analyzed [1,2]. In contrast, we use a Gaussian signal assumption rather than a weak signal assumption, deriving limiting cases of the detector, and considering incompletely known statistics of signal and noise.

The development is based on discrete-time models of signal and noise as zero-mean complex Gaussian processes with independent and identically distributed real and imaginary parts. The autocovariance matrix of the signal vector **X** is C, which is positive definite and Hermitian, but not Toeplitz. The noise vector **Z** has autocovariance matrix F, which is positive definite, Hermitian, and Toeplitz. Under the null hypothesis, the observation is **W=Z**, while under the alternative hypothesis, the observation is **W=X+Z**. If the statistics of signal and noise are completely known (including the cycle frequencies and phases of the signal, and the power of the signal and the noise), the log-likelihood ratio test yields a sufficient statistic $\lambda(\mathbf{W})=\mathbf{W}^{H}L\mathbf{W}$ with linear operator $L=F^{-1}CF(F+C)^{-1}F^{-1}$. Manipulation of this expression yields interpretation of $\lambda(\mathbf{W})$ as a sum of terms that include a radiometer and a coherent multicycle detector. When the signal is weak, $\lambda(\mathbf{W})$ corresponds to the result derived using a maximum-deflection argument [2]. Yet for stronger signals, the likelihood ratio detector differs from the maximum-deflection detector.

If the time-origin of the signal is constant but unknown, it can be modeled as a random variable uniformly distributed over the period of cyclostationarity, and the resulting likelihood ratio test does not exploit the cyclostationarity of the signal. If the stationary statistics of the observation are the same under both hypotheses, the likelihood ratio test for cyclostationarity in the observation is a coherent multicycle detector, assuming all cyclostationary statistics are known. In some cases, detection performance can be predicted analytically from this formulation.

REFERENCES

[1] C.K. Chen, (1989) "Spectral Correlation Characterization of Modulated Signals with Application to Signal Detection and Source Location," *Ph.D. Dissertation*, University of California, Davis, March 1989.

[2] W.A. Gardner, (1988) "Signal Interception: A Unifying Theoretical Framework for Feature Detection," *IEEE Transactions on Communications*, Vol. 36, pp. 897-906, August 1988.

[3] N.F. Krasner, (1982) "Optimal Detection of Digitally Modulated Signals," *IEEE Transactions on Communications*, Vol. 30, pp. 885-895, May 1982.

Work supported by the MITRE-Sponsored Research Program.

IN-PHASE AND QUADRATURE PAM SELF-NOISE: BENEFICIAL EFFECTS OF SPECTRAL CORRELATION ON SYNCHRONIZATION

Nelson M. Blachman
GTE Government Systems Corp.
Mountain View, CA

The clock waveform of a PAM signal may be recovered by feeding a nonlinear function (e.g., the square) of that signal to a narrowband filter. The deterministic relationship between pairs of spectral components of the PAM signal whose frequencies differ by or sum to a multiple of the clock frequency has opposite effects on the in-phase and the quadrature components of the output of such a narrowband filter centered on a harmonic m/2T of half the clock frequency. The mean squared value of the component in quadrature with the clock harmonic determines the mean squared phase error (jitter) in the clock waveform regenerated in this way when m is even (usually m=2). This mean squared value is studied as a function of the narrowband filter's shape, bandwidth, and center frequency--first for the PAM signal itself and then for its square, whose behavior is remarkably similar--thus clarifying and extending previous work on this topic.

PROGRESS ON MAXIMUM LIKELIHOOD TDOA ESTIMATION FOR CYCLOSTATIONARY SIGNALS

Marc Brack
Motorola Government Electronics Group
Chandler, AZ

A transmitted signal s(t) is received at two separated remote locations with a time difference of arrival (TDOA) of D; noise is also received. Thus, let

$$x_1(t) = s(t) + n_1(t)$$
$$x_2(t) = s(t + D) + n_2(t). \tag{1}$$

Consider an observation of the two received signals over a period of T_{obs} seconds from which Fourier coefficients can be formed; denote these as $X_1(k)$ and $X_2(k)$.

For uncorrelated additive white Gaussian noise (AWGN) processes, the set of Fourier coefficients form joint Gaussian random variables. The probability density function (pdf) of the observation is then

$$p(\underline{X} \mid D) = c_G \exp\left(-\frac{1}{2}\underline{X}^H \underline{G}^{-1} \underline{X}\right) \tag{2}$$

where $\underline{X}$ is a vector formed from all Fourier coefficients and $\underline{G}$ is the cross-correlation matrix of the Fourier coefficients. Assuming that s(t) is cyclostationary, G can be decomposed as

$$\underline{G} = \begin{bmatrix} \underline{I} & 0 \\ 0 & \underline{E} \end{bmatrix} \begin{bmatrix} \underline{G}_S + \underline{G}_{n_1} & \underline{G}_S \\ \underline{G}_S & \underline{G}_S + \underline{G}_{n_2} \end{bmatrix} \begin{bmatrix} \underline{I} & 0 \\ 0 & \underline{E} \end{bmatrix}^H \tag{3}$$

where the matrices $\underline{G}_S, \underline{G}_{n_1}, \underline{G}_{n_2}$ are solely dependent on the cyclic spectrum of s(t), $n_1(t)$, and $n_2(t)$ (and therefore independent of D), I is the identity matrix and E is a diagonal matrix with elements

$$E[k,k] = \exp\left(j2\pi kD / T_{obs}\right). \tag{4}$$

When the exponent of equation (2) is expressed as a series of terms, the only term dependent on D is given by

$$J_D = -\underline{X}_1^H \mathrm{Re}(Q)\underline{E}\underline{X}_2. \tag{5}$$

Here, $\underline{X}_i$ is the vector of Fourier coefficients $X_i(k)$ and Q is dependent only upon $\underline{G}_s$, $\underline{G}_{n_1}$, $\underline{G}_{n_2}$ of equation (3). Since c_G in equation (2) is independent of D, maximizing the pdf relative to D to obtain the maximum likelihood (ML) estimate can be accomplished by minimizing $-J_D$. In doing this, equation (5) can be re-written to emphasize diagonal structure. The result is an algorithm similar to the SPECCOA method of Gardner and Chen where Q is used instead of using a single slice from the cyclic autospectrum of s(t) as in the SPECCOA algorithm. Empirical observation suggests that Q is the cyclic autospectrum of s(t). The ML estimate for a cyclostationary signal in AWGN appears to be a generalization of the SPECCOA method; a rigorous proof is being developed.

EIGENVALUE DISTRIBUTIONS OF CYCLOSTATIONARY SIGNALS

William A. Brown
Mission Research Corporation
Monterey, CA

Signal eigenvalues are of interest in connection with many detection and estimation problems. Understanding the eigenstructure of signals can sometimes provide insight leading to simpler implementations and performance analysis. This is especially true for problems involving stationary signals where eigenvalues can be simply related to the signal power spectrum for long time intervals. For cyclostationary signals, however, eigenvalues are not simply related to the power spectrum but depend on the signal cyclic spectrum in an apparently complicated manner.

As a motivating example, consider the problem of detecting the presence of a zero-mean Gaussian signal in white Gaussian noise. The log likelihood ratio contains a bias term, often incorporated into the detection threshold, which depends on the strength of the signal eigenvalues relative to the noise power spectral density. Explicit calculation of the bias is needed for setting the detection threshold and for calculating detection performance.

The signal eigenvalues are the eigenvalues of the integral equation $\lambda_i u_i(t) = \int_{-T/2}^{T/2} k(t,\tau) u_i(\tau) d\tau \; \{|t| \le T/2\}$ where $k(t,\tau)$ is the covariance of the signal of interest. For cyclostationary signals, the covariance function is periodic and the kernel of the integral equation can be expressed as a Fourier expansion. Of particular interest are the asymptotic properties of the eigenvalues and eigenfunctions as the observation time $T \to \infty$. For simplicity, suppose the signal is purely cyclostationary with integer period M and the observation time is an integer multiple of this period; $T = N = kM$. For sufficiently large T, incorporating the Fourier expansions of the kernel and the eigenfunctions transforms the eigen-system into $\lambda_i \mathbf{v}_i = \mathbf{S}\mathbf{v}_i$, where $\mathbf{v}_i$ is an eigenvector consisting of the Fourier coefficients of the eigenfunction $u_i(t)$, and $\mathbf{S}$ is an infinite dimensional *cyclic spectrum matrix* with elements $S_{mn} = S_s^{(m-n)/N}((m+n)/2N)$, where $S_s^{\alpha}(f)$ is the cyclic spectrum of the signal with cycle frequency α. The matrix $\mathbf{S}$ is sparse with non zero values only along the sub- or super-diagonals for which $m - n$ is a multiple of N/M.

Not surprisingly, a similar transformation exists for the discrete-time eigensystem $\lambda_i \mathbf{u}_i = \mathbf{K}\mathbf{u}_i$, where $\mathbf{K}$ is the N-dimensional signal covariance matrix. The unitary transformation $\mathbf{u}_i = \mathbf{W}\mathbf{v}_i$, where $W_{mn} = N^{-1/2} \exp(i2\pi mn/N)$ gives an equivalent system $\lambda_i \mathbf{v}_i = \mathbf{S}\mathbf{v}_i$ where $\mathbf{S} = \mathbf{W}^H\mathbf{K}\mathbf{W}$.

If N is sufficiently large and the signal is cyclostationary with integer period $M = N/L$, then S is an N-dimensional cyclic spectrum matrix with the elements given in the previous paragraph.

In order to learn something about the eigenstructure of communication signals, the eigenvalues and eigenvectors were computed for three signal types; a stationary signal, QPSK, and BPSK. Each of the signals had an identical power spectrum but a distinct cyclic spectrum and in each case $N = 128$. For the stationary signal, the eigenvectors approach sine waves at bin frequencies n/N over the band of frequency support of the signal. If the eigenvectors are ordered according to their peak spectral frequency, the corresponding eigenvalues trace out the signal power spectrum versus frequency. However, for QPSK and BPSK the ordering of eigenvalues is ambiguous because many eigenvectors possess two or more frequency components of comparable strength. With an ordering scheme similar to that for the stationary signal case, the eigenvalue distributions become more concentrated as the degree of cyclostationarity increases. For example, BPSK has fewer but larger eigenvalues than does QPSK.

The sparse highly structured form of the cyclic spectrum matrix can certainly be exploited for efficient computation of the eigenvalues. However, a better understanding of the eigenstructure of cyclostationary signals will result if a simple asymptotic or approximate relationship between the cyclic spectrum and the eigenstructure can be discovered.

USE OF CYCLOSTATIONARY FEATURES IN FREQUENCY HOPPING SIGNAL SEGMENT ASSOCIATION

Douglas Cochran and Scott Enserink
Department of Electrical Engineering
Arizona State University
Tempe, AZ

When a slow frequency hopping spread spectrum communication signal is intercepted by a broadband receiver, numerous obstacles must be overcome to obtain the transmitted message from the received data. Assuming an initial segment of a signal of interest (SOI) is identified by the interceptor and a hop is detected, it is generally difficult to properly identify which signal in a cluttered spectrum is the continuation of the original SOI segment. The situation is even worse in the presence of synchronously hopping signals (e.g., with multiple access frequency hopping systems). Because several signals share the same hopping times, segment start and stop times are of little value in segment association. Moreover, following a hop, a signal not of interest (SNOI) to the interceptor can occupy the frequency slot previously held by the SOI while the SOI appears in a new frequency slot.

The purpose of this presentation was to demonstrate the feasibility of frequency hopping signal segment association based on cyclostationary signal processing. Examples were shown in which the use of cyclic spectral characteristics allows correct association of frequency hopping signal segments in a cluttered environment where association algorithms based on more traditional measurements (bandwidth estimates, specral shape, segment start/stop time estimates, signal strength, etc.) were not effective. In the examples shown, estimates of keying rates and modulation types of the various signal segments detected were used as association parameters.

REFERENCES

[1] W.A. Gardner, (1988) "Signal Interception: A Unifying Theoretical Framework for Feature Detection," *IEEE Transactions on Communications*, Vol. COM-36(8), pp. 897-906, August 1988.

[2] W.A. Gardner and C. M. Spooner, (1988) "Cyclic Spectral Analysis for Signal Detection and Modulation Recognition," *Proceedings of the IEEE Military Communications Conference*, pp. 24.2.1-24.2.6, San Diego, October 1988.

CARRIER-FREQUENCY ESTIMATION OF BPSK AND QPSK SIGNALS USING SPECTRAL-LINE TECHNIQUES

Bruce J. Currivan
Stanford Telecom
Santa Clara, CA

A method for carrier frequency estimation of continuous wave (CW), binary phase shift keyed (BPSK), or quaternary phase shift keyed (QPSK) signals utilizes a parabolic interpolator as shown in Figure 1.

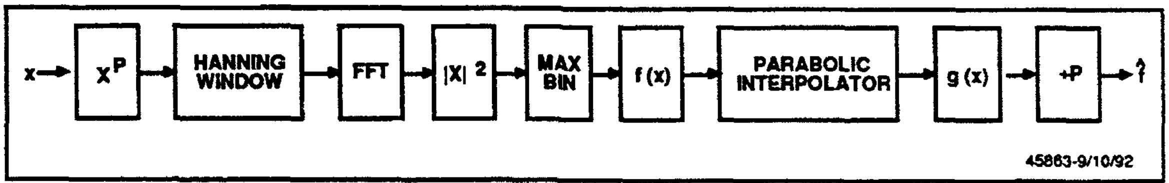


Figure 1. Frequency Estimation Algorithm

Complex baseband samples are raised to the P^{th} power, where $P = 1, 2,$ or 4 for CW, BPSK, or QPSK, respectively, to remove the modulation and produce a spectral line at P times the carrier frequency. The signal is then Hanning windowed to spread the spectral line into 3 correlated bins to enhance the operation of the interpolator. An FFT is taken and the power in each bin is calculated. The maximum-power bin and its immediate upper and lower neighboring bins are applied to a nonlinearity f(x) whose purpose is to match the window spectrum to a parabola. The three bins are then applied to a parabolic interpolator. The result is applied to a nonlinearity g(x) to remove the known bias in the interpolator (g(x) may be determined empirically). The result is then converted to frequency units, divided by P, and output as the frequency estimate.

The parabolic peak interpolator computes a fraction Δx which indicates the estimated offset of the peak from the maximum bin. Its equation is

$$\Delta x = \frac{y_2 - y_0}{2(2y_1 - y_2 - y_0)}$$

Δx is then added to the index x_1 of the maximum bin.

Where:

Δx = interpolator offset in frequency bins, range (-1,1)

(x_1,y_1) represents the frequency bin x_1 and power y_1 of the FFT peak; x_1 is in the range (0,N-1)

(x_0,y_0) is the neighboring point below the peak frequency

(x_2, y_2) is the neighboring point above the peak frequency

Using $f(x) = \log x$ and $g(x) = x$, the interpolator was found to be accurate to 1.6% of an FFT bin. Future work will investigate optimal choices for $f(x)$ and $g(x)$ as well as noise performance.

ESTIMATION OF SOME SPECTRAL FUNCTIONAL PARAMETERS OF WIDE SENSE ALMOST CYCLOSTATIONARY PROCESSES

Dominique Dehay
IRMAR, Campus de Beaulieu
Rennes, FRANCE

A wide sense almost cyclostationary process (also named almost periodically correlated and denoted apc) is a process $X : R \to L^2_C(\Omega,\mathcal{A},P)$ such that for any t the function $s \to K(s+t,s) = E\left(X(s+t)\overline{X(s)}\right)$ is almost periodic in the sense of Bohr. Under some weak regularity conditions the covariance kernel K admits a Fourier series decomposition, $K(s+t,s) \sim \sum_{\alpha \in R} b_\alpha(t) e^{is\alpha}$, whose coefficient functions b_α are the Fourier transforms of complex measures m_α, $\alpha, \in$ **R**, which are absolutely continuous with respect to the measure m_0 [3,4]. Considering apc strongly harmonizable processes, the spectral covariance of the process (its spectral bimeasure) can be expressed in terms of these complex measures m_α.

The estimation of the coefficient functions $b_\alpha(t)$, and of the spectral density function $f_\alpha(\lambda)$ whenever m_α is absolutely continuous with respect to Lebesgue measure, can be considered from a sample path of the process. Some modifications of the usual estimators for the second order stationary situation provide consistent estimators under different types of hypotheses: in terms of conditions on the stochastic spectral measure associated with X [1], or of regularity conditions on b_α or f_α, for strongly harmonizable Gaussian apc processes [3], or in terms of ϕ-mixing conditions for some more general apc processes [5,2]. The estimators of f_α are smoothed shifted periodograms and some rates of convergence can be stated.

REFERENCES

[1] D. Dehay: Hab. Dir. Recherches, Univ. Sc. Tech. Lille (1991).

[2] D. Dehay: C.R. Acad. Sc. Paris, 314(4) 313-316 (1992).

[3] D. Dehay: preprint (1991).

[4] H.L. Hurd: J. Multivariate Anal., 37(1) 24-45 (1991).

[5] H.L. Hurd and J. Leskow: Stat. Prob. Letters, 14(1) 299-306 (1992).

SIGNAL QUALITY ESTIMATION WITH EXTENSIONS TO SIGNAL DETECTION

Robert D. Favorite
HRB Systems, Inc.
State College, PA

Signal processing laboratories receive signal intercepts of all levels of fidelity (i.e., signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR)). Knowledge of the quality of an intercept is essential in determining the appropriate processing technique(s) to employ for signal conditioning and demodulation. Often, true signal quality is not understood until an initial demodulation run is completed.

This briefing describes a technique for signal quality assessment which operates independently of signal demodulation. Thus it can be used as a pre-scan operation prior to actually processing the signal. The results of the pre-scan can aid in determination of the type of processing required to recover data from the signal intercept. It can also be used to generate a quality profile (quality versus time) over the duration of the intercept.

The technique is based upon measuring the second central moment of the phase of the baud rate feature in the spectral correlation density (SCD) of the signal of interest. The measurement technique computes multiple cuts of the SCD baud rate feature, the cuts being spaced uniformly in time. The phase versus frequency component of each cut is examined and a linear fit of phase over time is computed for each frequency bin of the phase versus frequency component. The mean squared error (MSE) of the fit is examined on a bin-by-bin basis. Low MSE indicates the presence of a valid cycle frequency feature. The SNR of the feature and, therefore, the SNR of the original signal is inversely proportional to the value of the MSE. Contiguous bins of low or like MSE define the bandwidth of the feature.

Signal amplitude is estimated from the average magnitude of the cycle frequency feature. SIR is estimated by comparing the square of the signal amplitude to the total energy in the environment which is obtained from a summation over the zero-alpha cut.

An extension of this technique to signal detection is achieved by thresholding the MSE of the phase fit. The threshold is set at or slightly above the MSE value corresponding to the minimum processable signal quality.

HARDWARE SYSTEM IMPLEMENTATIONS OF QUADRATIC PROCESSING

Keith R. Frampton
Information Systems Division
Essex Corporation
Columbia, MD

The paper presents three hardware system implementations of quadratic processing. Two of the systems use a combination of acousto-optic and digital technology and the other is a software implementation operating on commercial off-the-shelf hardware.

The first system is a quadratic processing breadboard which implements high speed, wideband quadratic functions for the purpose of wideband spectral analysis. It was designed as a 3' x 5' optical breadboard for the purpose of generating the following quadratic functions in real time:

1 Cross ambiguity function (CAF),
2 Cross Wigner-Ville function (CWF),
3 Cyclic spectrum (CS),
4 Mellin correlations.

The second system is also a high speed, wideband quadratic processor for the purpose of wideband spectral analysis. The system was designed and manufactured as an engineering brassboard and contains an acousto-optic quadratic processor and custom VLSI technology. It was developed as a next generation of the breadboard system described above in a reduced package size.

The third system is a digital quadratic processing implementation in the form of a workstation-based TDOA/FDOA parameter estimation system. It provides reasonable throughput/latency with commercial off-the-shelf hardware. The system uses a Sun workstation with Sky Warrior array processors for the high speed computations.

The paper describes each of these three systems.

TRANSMITTER DESIGN FOR DATA TRANSMISSION IN THE PRESENCE OF A DATA-LIKE INTERFERER

Glen D. Golden, James E. Mazo, and Jack Salz
AT&T Bell Laboratories
Holmdel, NJ

In many digital communications systems, crosstalk, rather than additive stationary noise, is the primary channel impairment. In such systems it is known that the optimum transmitter is not, in general, Nyquist bandlimited, in contrast to the case for the additive noise channel. Loosely speaking, this is because the wider-than-Nyquist transmitted signal results in crosstalk which is cyclostationary, and thus spectrally redundant. This redundancy allows the receiver to induce some degree of self-cancellation of the crosstalk which more than compensates for the reduced transmitted spectral density of the higher bandwidth signal.

Nevertheless, the problem of optimally choosing the transmitter shaping function for the crosstalk channel is a difficult one, and has so far remained unsolved. Motivated by current forward-looking interest in the high-speed digital subscriber loop (HDSL) and related crosstalk-dominated applications, we attack a subcase of this problem in which only a single interferer is present. We are able to solve this problem optimally for the zero-forcing receiver. This result is then used to obtain a numerical algorithm for designing practical near-optimum transmitters for use with real-world minimum mean-squared error (MMSE) receivers.

When applied to HDSL-like systems with a single (or dominant) interferer, our analysis and numerical results confirm that wider-than-Nyquist transmitters provide a large performance advantage over Nyquist-limited transmitters. Several interesting and counter-intuitive results also arise. For example, we find that PAM and QAM differ considerably in their performance over the crosstalk channel, despite their essential equivalence in additive stationary noise. We also show how certain characteristics of the HDSL channel can be exploited using symbol rate optimization: Adjusting the symbol rate permits the creation of extra Nyquist zones in a given fixed bandwidth, thereby enhancing the degree of cyclostationarity of the transmitted signal, and consequently improving the crosstalk mitigation at the receiver. Finally we note that HDSL performance with a single interferer is not likely to be a sensitive function of the details of either the channel or the transmit filter as long as certain general shaping considerations are observed. The latter result facilitates the design of practical, fixed (compromise) transmitters capable of near-optimum performance over a broad class of qualitatively similar channels.

HIGHER ORDER CUMULANTS AND CUMULANT SPECTRA

Melvin J. Hinich
Applied Research Laboratories
The University of Texas at Austin

Higher order cumulant spectra are destined to play an important role in the development of signal processing methods in the coming years. A number of interesting papers have already been published on signal processing applications of the bispectrum, which is related to the third order cumulant spectrum. The n^{th} order cumulant spectrum of a sampled random time series is the n dimensional Fourier transform of the n^{th} cumulant of the joint density of n successive observations of the series.

In this paper, an exposition of joint cumulants and cumulant spectra is presented. A distinction is emphasized between the cumulant spectrum of a time series and its stationary version, here called a *polyspectrum*. Then the variance and covariance of the sample bispectrum is derived using a relationship between cumulant spectra of the finite Fourier transform for the 2^{nd} and 4^{th} cumulant, and the bispectrum and trispectrum of the time series.

MULTIPLE-SCAN SPECTRAL-COHERENCE PROCESSING OF PERIODICALLY-CORRELATED SIGNALS

Harry L. Hurd and Carl H. Jones
Harry L. Hurd Associates
Raleigh, NC

This paper examines methods to improve the detection and characterization of cyclostationary signals whose modulation structure is not sufficiently stable to permit arbitrarily long coherent integration. Two basic methods are considered.

The first method begins with short-time estimates of the bifrequency coherence surface. The magnitude-squared coherences are combined to provide a single time-averaged estimate of the coherence surface. This method is suitable for signals whose cycle frequencies remain relatively constant but are not sufficiently stable to allow analysis with long transforms.

The second method also begins with short-time estimates of the bifrequency coherence surface. Each estimate is collapsed into a one-dimensional statistic. These statistics are then arranged in time sequence to provide a time versus cycle frequency display. This method is applicable to signals with large (but slow) variation in their modulation structure.

We find that both procedures can provide significant qualitative improvement in detection performance. However, care must be taken when setting display and detection thresholds for averaged coherence values. In particular, the presence of a cyclostationary signal can increase the observed values of coherence at all cycle frequencies--not just the cycle frequencies associated with the signal. Although this effect does not seem to be significant when individual coherence surfaces are displayed, it becomes important when the variance of the coherence estimates is reduced by averaging. As a result, thresholds calculated for a particular false-alarm rate under the assumption of stationary, Gaussian noise can prove inadequate when cyclostationary signals are present.

PROGRESS IN CYCLOSTATIONARY-SIGNAL PROCESSING

Mark F. Kahn, Noel B. Whitley, and Thomas E. Biedka
E-Systems, Inc.
Greenville Division, TX

In this paper we present three new techniques for processing low probability of intercept (LPI) signals exhibiting cyclostationarity. The methods developed here include the Modified FFT Accumulation Method (MFAM), the Short-Time Cyclic Periodogram Matched Filter (STCPMF) and the Cyclic-Spectral MUSIC technique. Together these techniques provide a frequency domain approach to the problems of signal detection and time-of-arrival and direction-of-arrival estimation. A performance evaluation for each of the techniques is presented in the form of Monte Carlo simulation results. In addition, an existing hardware/software system implementation is discussed, revealing feasibility of application for the new techniques.

The MFAM technique is a direct modification of the previously developed FAM approach for estimation of a signal's spectral correlation function. Three modifications are presented including a data preprocessing stage, a secondary FFT interpolation stage, and a frequency smoothing post-processing stage. Together with the appropriate choice of window functions, the technique is shown to provide improved estimation reliability with a more complete coverage of the bifrequency plane. Successful detection performance at low SNRs is demonstrated for systems requiring significant narrowband interference excision as well as search systems with errors in receiver tuning or insufficient input bandwidth.

The STCPMF is a technique for estimating the time-of-arrival (TOA) or time-of-departure (TOD) for burst or transient signals exhibiting cyclostationarity. The technique employs a sliding window cyclic spectral correlation estimate with a matched filter output. A simple threshold test is then used to determine the presence of a leading or trailing edge. Time-varying cyclic spectral correlation surfaces are estimated for both simulated and actual hybrid-FH/DS spread spectrum communications. TOA estimation accuracy is then evaluated via Monte Carlo simulations and compared with the more conventional frequency doubler and frequency quadrupler techniques. It is demonstrated that the STCPMF may outperform the more conventional techniques at low negative SNRs.

The Cyclic-Spectral MUSIC technique is a straightforward modification of the Cyclic MUSIC approach. In this new technique, entries in the cyclic autocorrelation matrix are replaced by cyclic spectral cross-correlation estimates. As such, the technique is able to exploit spectral selectivity not available in conventional Cyclic MUSIC. In addition, with the use of cyclic spectral correlation

estimates there is no longer a requirement for determining an appropriate cyclic autocorrelation lag parameter. Monte Carlo simulations indicate that direction-of-arrival estimation performance of Cyclic MUSIC and Cyclic-Spectral MUSIC is comparable for a wide range of signal environments, with Cyclic Spectral MUSIC providing slightly better estimation accuracy for longer data collects. Performance is characterized for systems employing narrowband interference excision, and environments with spatially coherent Gaussian noise, and compared to the conventional MUSIC technique.

This effort partially funded by Rome Laboratory, Rome, NY.

A HIGH PERFORMANCE WORKSTATION FOR SPECTRAL CORRELATION ANALYSIS

Carolyn T. Koenig and Teri L. Archer
Signal Science, Inc.
Santa Clara, CA

Spectral correlation analysis offers a unified approach to important aspects of modulated signal processing. The spectral correlation surface provides a more complete characterization of modulated signals. Features appear on the spectral correlation surface which can distinguish signals whose conventional spectra are identical. Because of this ability the spectral correlation analyzer (SCA) is useful for detection and parameter estimation of spectrally overlapping signals. To overcome the limitations of conventional computer implementations, a high speed workstation has been created to enable spectral correlation algorithms to be tested in multiple environments. The SCA workstation is also a useful tool for design and testing of efficient modulation schemes. The cycle frequency, or alpha, parameter provides another dimension that can be exploited in developing signaling formats. The increasing demand for communications services, including cellular communications and personal communication networks, results in a more crowded spectrum. Spectral correlation analysis can contribute to the development of efficient modulation and reception algorithms that will lead to more efficient spectral use.

Development and testing of spectral correlation processing algorithms for single and dual channel signal data have been performed to provide a basis for the SCA workstation. Results show that the performances of spectral correlation and cyclic TDOA algorithms are improved by including preprocessing methods which reduce cochannel interference. Algorithm testing has used both computer simulated input data and digital snapshots of actual modulated signals. The signal modulation types include digital phase and amplitude modulation formats, including several PSK and QAM formats. Preprocessing to reduce cochannel interference leads to more reliable estimates. After preprocessing, features in the cyclic spectrum corresponding to the interfering signals are reduced so that features due to the desired signal are more apparent. Another benefit is that the amount of data required to calculate reliable estimates of the surface or TDOA is decreased. This reduces computational requirements and improves the timeliness of cyclic spectrum or TDOA estimation.

The SCA workstation allows continuous, real time cyclic spectrum computations. Calculations of the spectral correlation surface have previously been performed offline on snapshots of data. The workstation combines the Sun SPARC 10 computer for user interface and spectral correlation surface display with a Mercury coprocessor for high speed computations. Analysis and manipulation of the spectral correlation surface is supported by state-of-the-art multidimensional data display software. The SCA workstation is a tool for signal analysis as well as for development of signal processing methods which exploit cyclostationarity.

REALIZATION OF TDOA ESTIMATION ARCHITECTURES

Herschel H. Loomis, Jr. and Raymond Bernstein
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA

An architecture for the computation of time difference of arrival (TDOA) estimates using spectral correlation based algorithms SPECCOA and SPECCOR is proposed [1,2]. The structures of the various principal components are developed and a complexity analysis is piesented. From this analysis it is determined that the most hardware complexity is required for the computation of $\hat{S}_x^\alpha(f)$ for all f and α in order to identify the value(s) of α for which good signal-cyclostationarity features exist to which the cyclic TDOA computing algorithm of choice can be applied. It is demonstrated that the Strip Spectral Correlation Analyzer is the most efficient algorithm for computing $\hat{S}_x^\alpha(f)$. Frequency smoothing methods are shown to be the best for computing the cross spectral correlation function $\hat{S}_{yx}^\alpha(f)$. It is also shown that SPECCOA is superior to SPECCOR in hardware complexity and in speed. Realization using pipeline FFT and vector processing chips is considered in detail, and the tradeoff between the *real time factor* [3] and hardware complexity is examined.

REFERENCES

[1] W.A. Gardner and C.K. Chen, (1992) "Signal-Selective Time-Difference-of-Arrival Estimation for Passive Location of Manmade Signal Sources in Highly Corruptive Environments. Part I: Theory and Method," *IEEE Transactions on Signal Processing*, Vol. SP-40(5), pp. 1168-1184, May 1992.

[2] C.K. Chen and W.A. Gardner, (1992) "Signal-Selective Time-Difference-of-Arrival Estimation for Passive Location of Manmade Signal Sources in Highly Corruptive Environments. Part II: Algorithms and Performance," *IEEE Transactions on Signal Processing*, Vol. SP-40(5), pp. 1185-1197, May 1992.

[3] W.A. Brown and H.H. Loomis, Jr., (1993) "Digital Implementations of Spectral Correlation Analyzers," *IEEE Transactions on Signal Processing*, 1993 (in press).

REMARKS ON PERIODICALLY CORRELATED PROCESSES AND PERIODICALLY DISTRIBUTED SEQUENCES

A. Makagon and H. Salehi
Department of Statistics and Probability
Michigan State University
East Lansing, MI

A.G. Miamee
Department of Mathematics
Hampton University
Hampton, VA

The poster contains a survey of results from the following three papers:

[1] A. Makagon, A.G. Miamee and H. Salehi, (1993) "Continuous Time Periodically Correlated Processes: Spectrum and Prediction," submitted for publication.

[2] A. Makagon, A.G. Miamee and H. Salehi, (1991) "Periodically Correlated Processes and Their Spectrum: a Survey," to appear in *Proceedings of NASA/Hampton University Workshop on Nonstationary Random Processes,* Hampton, VA, 1991.

[3] A. Makagon and H. Salehi, (1993) "Structure of Periodically Distributed Stochastic Sequences," to appear in *Kallianpur Festschrift.*

In papers [1] and [2] a rigorous mathematical treatment of the spectrum and random spectrum of bounded (not necessarily continuous) periodically correlated (PC) processes is provided. The existence of a harmonic series representation and regularity properties of PC processes are discussed. Paper [3] deals with periodically distributed sequences, which can be viewed as an analog of PC sequences in the absence of the second moments. This paper contains a representation of an arbitrary PD sequence in the form of a harmonic sum of components of an associated strictly stationary sequence. This representation is similar to the well-known representation of PC sequences obtained by Gladyshev (Soviet Math. Dokl. 2, 1961).

COMPLETENESS OF THE SPECTRAL DOMAIN OF PERIODICALLY CORRELATED PROCESSES

A.G. Miamee
Department of Mathematics
Hampton University
Hampton, VA

Completeness of the spectral domain of stationary processes, which is well-known, has been essential for the development of a comprehensive theory for these processes. For non-stationary harmonizable processes this completeness question is equally important. This question which was open for some time has recently been investigated by several authors. It is now evident that, in general, the spectral domain of a harmonizable process does not need to be complete. In this note we show that the spectral domain of any periodically correlated processes is actually complete. This result should help to get a more complete picture of the theory of this important class of non-stationary processes.

This research was supported by NASA Grant No. NAG-1-768, ONR Grant No. N00014-89-J-1824, and U.S. Army Research Office Grant DAAL 02-91-G-0238.

TIME-FREQUENCY REPRESENTATION OF CYCLOSTATIONARY SIGNALS

Joel M. Morris
Electrical Engineering Department
University of Maryland
Baltimore, MD

In this presentation we showed that certain classes of cyclostationary signals, or the non-cyclostationary components of others, can have their 2^{nd}-order representations in the autocorrelation domain $\big((t,\tau)$-domain$\big)$, cyclic autocorrelation domain $\big((\alpha,\tau)$-domain$\big)$, Wigner-Ville domain ((t,f)-domain), and Bispectrum domain $\big((\alpha,f)$-domain$\big)$ decomposed into separate summations of autoterms and crossterms. This work is an extension of similar work in decomposing the Wigner-Ville distribution and the Ambiguity function [1,2]. This partition or decomposition is achieved via representing arbitrary finite energy continuous-time, or finite/periodic discrete-time, signals with Gabor expansions. In particular, for discrete-time signals $s(i) = x(i) + \eta(i)$, either stochastic or deterministic, having a cyclostationary component $x(i)$ and a non-cyclostationary component $\eta(i)$, $R_x(i,\tau)$ (in symmetric form) is periodic with period N_o, and

$$R_x^{\alpha/N_o}(\tau) = \lim_{N\to\infty} \frac{1}{2N+1} \sum_{i=-N}^{N} x(i+\tau)x^*(i-\tau)e^{-j2\pi i\alpha/N_o} \neq 0 \quad \text{for some } \alpha$$

can be expressed as: (1) a summation of weighted Gaussian terms with complex modulation and centered at (0,0) in the (α,τ)-domain (autoterms), and (2) a summation of weighted Gaussian terms with complex modulation and centered away from (0,0) in the (α,τ)-domain (crossterms). The weights are pair products, or squared magnitudes, of Gabor coefficients from the discrete Gabor expansion of $x(i)$ [3]. A similar (α,τ)-domain decomposition representation exists for $R_\eta(i,\tau)$, which would be particularly useful when $\eta(i)$ is nonstationary. Such a decomposition: (1) allows for the isolation of the autoterms or crossterms when desired, and (2) provides new information and perspective to facilitate signal analysis and synthesis, and the design of joint time-frequency filters and other joint time-frequency representations.

REFERENCES

[1] J.M. Morris and D.S. Wu, (1992) "Some Results on Joint Time-Frequency Representations via Gabor Expansions," *Proc. 26th Conf. Inform. Sci. and Sys.*, Vol. 1, pp. 6-10, Princeton Univ., Princeton, NJ, March 18-20, 1992.

[2] J.M. Morris and D.S. Wu, (1993) "On the Ambiguity Function: Decomposition and Discrete Forms," submitted for publication.

[3] J. Wexler and S. Raz, (1990) "Discrete Gabor Expansions," *Signal Processing,* Vol. 21(3), November 1990, pp. 207-220.

A CYCLIC PRONY ALGORITHM WITH AUTOMATIC BANDWIDTH SELECTION FOR MULTIPATH-CHANNEL IDENTIFICATION

Antonio Napolitano and Luigi Paura
Dipartimento di Ingegneria Elettronica
Università di Napoli "Federico II"

The multipath-channel identification problem arises in many application areas, such as radar, sonar, ocean acoustics, data transmission, etc.. The problem can be modeled as:

$$x(t) = s(t) + n(t)$$
$$y(t) = \sum_{k=1}^{N} a_k s(t - d_k) + m(t)$$

where x(t) and y(t) are measurements at the input and the output of the channel, s(t) is the real exciting signal (ES), and n(t) and m(t) account for the presence of noise plus interference which are assumed independent (over time) of s(t). The scaling amplitudes a_k and the arrival times d_k (AAT's) are the parameters to be estimated. Recently a new approach, proposed in the time-difference-of-arrival context, has been applied to AAT estimation in order to overcome the limits of the generalized cross-correlation (GCC) methods which provide very poor performances when the interfering signals are comparable to, or greater than, the exciting signal in spectral density level and bandwidth and/or exhibit a high degree of temporal correlation amongst themselves. The proposed algorithms assume that the ES exhibits cyclostationarity, which occurs for essentially all modulated signals encountered in radar, sonar and communication applications. They assure high tolerance against noise and interference also when n(t) and m(t) are correlated with one another. In particular, a modified version of the Prony algorithm (the improved cyclic Prony method) based on measurements of cyclic spectra has been proposed to obtain, at the same time, high temporal resolution and accurate amplitude estimation.

All the proposed methods based on the cyclic spectrum properties (cyclic methods) assume that there exists at least a cycle frequency α for which the ES exhibits cyclostationarity, but for which the interference plus noise n(t) and m(t) do not individually or jointly exhibit cyclostationarity. There are interference environments, however, where such an assumption is not valid. The present paper extends the improved cyclic Prony method previously proposed to the case where this assumption cannot be made. It is here assumed that there exists a limited frequency interval where a cyclic spectrum of the ES does not overlap with both the cyclic spectrum of the input interference and the cyclic cross-spectrum of the input and output interferences. A procedure which automatically selects such a frequency interval and then applies the improved cyclic Prony method is presented. Results of simulation experiments show the effectiveness of the algorithm in severely corruptive noise and interference environments.

MAXIMUM ENTROPY MODELS FOR NONSTATIONARY PROCESSES

Mohsen Pourahmadi
Division of Statistics
Northern Illinois University
DeKalb, IL

We show that maximum entropy (ME) problems for periodically correlated (PC, cyclostationary) and multivariate stationary processes are closely related to each other. By using an extension of Burg's result to multivariate stationary processes we obtain PC models that have ME; these are in fact periodic AR(p) processes introduced by Brelsford and Jones (1967). Many difficulties encountered in solving ME problems for PC processes are prototypical of those encountered when dealing with generally nonstationary processes with autocovariances given over nonrectangular regions. Regarding a PC or a d-variate stationary process X_t the following problem is open at the moment: Given some (not all) entries of $\gamma_k = \text{cov}(X_{t+k}, X_t)$, $k=0, \ldots, p$, find a d-variate stationary process with ME having these (incomplete) covariances.

CLASSIFICATION OF CYCLOSTATIONARY SIGNALS

Bart F. Rice, Scott R. Smith and Richard A. Threlkeld
Lockheed Missiles and Space Company, Inc.
Sunnyvale, CA

The cyclostationary "signature" of a signal can be used to classify the signal into one of a number of predefined categories. An automatic modulation recognizer is described which makes use of a set of features consisting of "structure coefficients" which are computed on the outputs of various non-linear processes to which the target signal is subjected.

Cyclostationarities of a signal manifest themselves as spikes in the spectra of various nonlinear processes. The output of such a process may be regarded as having "high structure." In contrast, a time series which contains no dominant spectral components may be said to have "low structure." The amount of structure in a data sequence can be captured in a "structure coefficient" (SC), which has a value near 1 if the sequence contains a small number of dominant frequencies and is near 0 if its spectrum contains no significant "discontinuities."

The notion of a SC is based on the fact that the Fourier transform of an impulse is a sinusoid, with the energy uniformly distributed in the transform domain. Thus the FFT of a time series with just one or two prominent peaks manifests a large proportion of the energy of the time series at high frequency, whereas "non-peaky" time series have considerably less high frequency energy. A prescription for computing SCs is as follows: (1) compute the FFT of the time series; (2) compute the centroid of the FFT magnitudes and divide by 0.5 x FFT length; (3) "clip" the normalized centroid if it exceeds 1.0.

An automatic classifier which illustrates the principles described above has been developed and has been tested on simulated signals. All but one of the signal features are SCs. The signal features are: (1) duty cycle (fractional on-time estimate--to distinguish pulsed from continuous signals; this is the only feature which is not an SC); (2) SC for PSD of envelope; (3) SC for PSD of instantaneous frequency; (4) SC for PSD of delay-and-multiply; (5) SC for PSD of rectified frequency differences; (6) SC for PSD of signal squared; and (7) SC for PSD of signal 4^{th} power. The decision logic is implemented using the Probabilistic Neural Network which is a particularly convenient, easily trained, and powerful neural net paradigm which is well-suited to this application.

Eleven classes of signals have been successfully recognized using this technique, at signal-to-noise ratios (SNRs) down to about 4 dB. The minimum SNR at which the method will work depends on FFT size and number of FFTs averaged in making the SC computations. The classes are: (1) MSK; (2) 2-FSK; (3) 3-FSK; (4) BPSK (rectangular pulse shape); (5) BPSK (with pulse shaping); (6) square QAM (rectangular pulse shape); (7) square QAM (with pulse shaping); (8) non-square QAM; (9) PPM; (10) coherent pulse Doppler radar (may change PRF); (11) low capacity FDM/FM with pilot tone.

DETECTION OF CYCLOSTATIONARY SIGNALS IN A COCHANNEL INTERFERENCE ENVIRONMENT

Bart F. Rice, Edmund L. Soohoo, and Richard A. Threlkeld
Lockheed Missiles and Space Company, Inc
Sunnyvale, CA.

It is often useful to detect the presence of signals of interest (SOIs) even when the signals are so corrupted by cochannel interference that demodulation or extraction of information from the SOI is impractical. When the cyclostationary characteristics of both the SOI and the interference are known, such detection may be accomplished using the cyclic spectrum and enhancements thereto.

Approximately ten seconds of an FM audio signal in a TV band were digitized and stored. The recorded signal was considered to be typical of interference encountered by a number of SOIs. The signal was centered at an intermediate frequency of about 49 kHz and had a bandwidth of about 40 kHz. A BPSK signal was simulated and added at a level of about 7-8 dB below that of the recorded signal. The carrier frequency of the BPSK signal was 44 kHz and its symbol rate was 19.84 kHz. The cyclic feature at 19.84 kHz was clearly visible in the cyclic spectrum of the combined signals, even though the spectrum of the BPSK signal itself was completely obscured by the interferer.

"Causal" peaks (those corresponding to SOIs) need not be the highest ones in the cyclic spectrum, and they certainly were not in the case described, but if their location and shape are known they can be reliably detected. Detection may be enhanced by applying a filter in the f-direction of the cyclic spectrum which is matched to the shape of a causal peak, if it is known. The location in spectral frequency of the peaks provide an estimate of the SOI's carrier frequency. Peaks which lie along slope 1/2 "trend lines" are probably non-causal unless they are extremely strong. Good resolution in spectral frequency is often necessary to distinguish these from peaks corresponding to nearby (in spectral frequency) SOI cycle frequencies.

The "doubled-carrier" region of the conjugate cyclic spectrum of the combined signal was also inspected. The peak corresponding to the simulated BPSK signal was clearly visible. Since it appears at $\alpha = 2f_c$ (and f=0), a measurement of the carrier f_c is obtained which is accurate to within the α-resolution of the plot, which is generally much better than the resolution in the f-direction.

For typical α-resolution and f-resolution values used in the study, the major computations for the cyclic spectrum were 3×2^{16} 512-point FFTs, 41 2^{16}-point FFTs, and 30001 1024-point

FFTs. Without limiting the α-range, therefore, near-real-time detection is computationally tractable only on a supercomputer. The plotting software, done using X-windows, provided a variety of ways to visualize and interactively estimate parameters in the cyclic spectrum.

A TIME-FREQUENCY SMOOTHING ALGORITHM FOR CYCLIC SPECTRAL ANALYSIS

Randy S. Roberts
Los Alamos National Laboratory
Los Alamos, NM

Implementing cyclic spectral analysis algorithms, such as the Strip Spectral Correlation Algorithm or the Digital Frequency Smoothing Method, with fixed-size channelizers can force the designer to make undesirable tradeoffs in the frequency resolution, Δf, or the time-frequency resolution product, $\Delta t \Delta f$, of the estimate. One approach to alleviating these restrictions is to use hybrid smoothing algorithms. By providing independent control over the time and frequency resolutions, hybrid smoothing algorithms allow system designers to meet what appear to be conflicting requirements on values of Δf and $\Delta t \Delta f$.

The hybrid smoothing algorithm presented here smoothes first in time and then in frequency. The time-frequency smoothing algorithm is designed to compute estimates of the cyclic (cross) spectrum along lines of constant cycle frequency. The algorithm is based on the time-smoothing-with-decimation algorithm, but uses a fine-grain channelizer for input processing and incorporates frequency smoothing. Fine-grain channelization affords an opportunity to extract narrowband signals and provides greater control over the frequency resolution of the estimate than is provided by time smoothing alone. The computational efficiency of the time-frequency smoothing algorithm can be improved by applying the One Bit Spectral Correlation Algorithm (OBSCA). Using the OBSCA technique, complex multiplications in spectral correlation operations are reduced to data multiplexing and sign change operations. A scaling factor is required for a full implementation of the OBSCA, but satisfactory results can be obtained by using partial scaling.

A simulation study that evaluates the performance of the time-frequency smoothing algorithm with and without the OBSCA is presented. In the OBSCA simulations, results are presented for no scaling, full scaling, and partial scaling. The time-frequency smoothing algorithm produces accurate estimates of the cyclic features of a simulated BPSK signal. Using these estimates as a standard, the estimates produced by OBSCA with no scaling display distortion in the baudrate and carrier features, but the amount of distortion could be acceptable in some applications. Estimates produced by OBSCA with full scaling closely resemble the time-frequency smoothing results, except for a slight decrease in magnitude. Estimates produced by OBSCA with partial scaling show a slight amount of distortion, but again, the amount of distortion is minimal.

This work was supported in part by a contract from E-Systems Inc., Greenville Division, PI: W.A. Gardner).

CO-CHANNEL INTERFERENCE CANCELLATION VIA TRANSMIT PULSE SHAPE OPTIMIZATION IN DIGITALLY MODULATED SIGNALS

Sumit Roy
Department of Electrical Engineering
University of Pennsylvania
Philadelphia, PA

The problem of cross-talk or co-channel interference suppression is one that is of increasing importance in communication systems. In a series of seminal works, Gardner has developed and applied the theory of FREquency-SHift (FRESH) filtering to separation of co-channel signals by exploiting the (multiply-periodic) cyclostationary nature of digitally modulated waveforms. The optimum receiver is known to be linear (multiply) periodic time varying, and consists of several parallel branches--each consisting of frequency shifting by a cycle frequency of the received signal followed by LTI filtering. The outputs of all branches are summed and sampled at the baud rate to produce estimates of the transmitted digital data.

The situations to which FRESH filtering was applied and evaluated in Gardner's work consisted of cases where the interfering signals had distinct carrier frequencies and baud rates, and showed remarkable effectiveness in suppression of cross-talk. However, in many digital communications scenarios, this assumption is untenable due to system design. However, signal separation can still be achieved in this scenario if we assume that either carrier phases or transmit pulse shapes and/or symbol timing are distinct and that the system has sufficient excess bandwidth (specifically $\geq$ (N-1) 100% for N mutually interfering signals). In this work we focus on the effect of pulse shape optimization on interference suppression (ignoring any carrier phase and symbol timing offsets) based on a minimum MSE criterion. The fundamental result describes how the optimal transmit filter allocates power over the system bandwidth $[-N/2T, N/2T]$, and sample computations suggest that pulse shape optimization yields significant reduction in MSE.

EFFECTS OF MULTIRATE SYSTEMS ON WIDE SENSE CYCLOSTATIONARY INPUTS

Vinay Sathe
Communication Systems Research Lab
Tektronix Inc.
Beaverton, OR

P.P. Vaidyanathan
Department of Electrical Engineering
California Institute of Technology
Pasadena, CA

Multirate digital filtering is used in a variety of applications such as sub-band coding, voice privacy systems and adaptive filtering, to name a few. In multirate digital signal processing we encounter time varying linear systems such as decimators, interpolators and modulators. In many applications these building blocks are interconnected together with linear filters to form more complicated systems.

It is often necessary to understand the way in which the statistical behavior of a signal changes as it passes through such systems. While some issues in this context have an obvious answer, the analysis becomes more involved with complicated interconnections. For example it is easy to see that the decimated version of a wide-sense-stationary (WSS) signal remains WSS. But the following question is more complicated: if we pass a wide-sense-cyclostationary (WSCS) signal with period K through a fractional-sampling-rate-changing device, then what can we say about the stationarity (or otherwise) of the output? Is the answer to this question dependent on whether the low pass filter is ideal or not, and if so, how?

We answer questions of this nature for WSCS inputs. When we make transition from single rate to multirate systems, the assumption that signals are WSS is not valid even in theoretical studies. The reasons for the occurrence of WSCS in practical communication systems have been discussed in the literature. The results presented here show that even in a theoretical study of such systems, we shall find it more natural to assume that the signals are WSCS.

REPRESENTATION OF DISCRETE CYCLOSTATIONARY PROCESSES USING LINEAR PERIODICALLY TIME-VARIANT SYSTEMS

Moushumi Sen and Haluk Derin
Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA

This paper presents a characterization of discrete-time wide-sense cyclostationary (CS) processes [1] of single period as outputs of linear periodically time-variant (LPTV) systems. In [2] another approach to periodic system identification for continuous-time CS processes is presented. In this paper we make use of the equivalence between a CS process $x(n)$ of period P and a corresponding P-variate discrete stationary process $\mathbf{X}(n)$ to present a simpler factorization theorem for the rational spectral matrix $S_{\mathbf{X}}(z)$ of $\mathbf{X}(n)$:

Theorem 1. Let $S(z)$ be any $P \times P$ rational paraconjugate hermitian matrix of normal rank Q and n.n.d. on the unit circle $|z| = 1$,, having the form

$$S(z) = \mathbf{R}(0) + \sum_{n=1}^{M-1} \left[\mathbf{R}(n)z^{-n} + \mathbf{R}^*(n)z^{n}\right]$$

where $\mathbf{R}(n)$ are $P \times P$ matrices. Then, if $S(z)$ has a constant rank on the unit circle $|z| = 1$, there exists a $P \times Q$ matrix $\mathbf{G}(z)$ such that

$$S(z) = \mathbf{G}(z)\,\mathbf{G}^*(z)$$

where

(i) $\mathbf{G}(z)$ is a polynomial matrix of order $M-1$ in z^{-1},
(ii) The left inverse of $\mathbf{G}(z)$ is a $Q \times P$ rational matrix analytic in $|z| \geq 1$. □

The corresponding factorization theorem for continuous-time multivariate processes can be found in [3]. This enables us to show that every zero-mean CS(P) process $x(n)$ with a finite support autocorrelation function of length $2L-1$ $\left(\text{i.e., } r_x(n,m) = 0 \text{ for } |n-m| \geq L\right)$, can be modeled as the output of a finite impulse response causal and stable LPTV system $h(n,m)$ with white noise input $w(n)$, that is:

$$x(n) = \sum_{m=n-L+1}^{n} h(n,m)\; w(m).$$

In addition, if $x(n)$ is assumed to have full rank, i.e., if $S_X(z)$ is non-singular, then there also exists a corresponding periodic causal and stable IIR whitening filter $g(n,m)$ such that

$$w(n) = \sum_{m=-\infty}^{n} g(n,m)\ x(m).$$

Furthermore, if we remove the restriction on $x(n)$ that it have a finite support autocorrelation function, and instead assume that the spectral matrix $S_X(z)$ is rational in z, then we can show that a full rank CS(P) process $x(n)$ is linearly equivalent to its innovations process $w(n)$, i.e., each can be represented as the output of a causal and stable periodic IIR filter, with the other as the input.

In the latter stages of this work we became aware of [4] in which the above problem was addressed and solved in a slightly different manner.

REFERENCES

[1] W.A. Gardner and L.E. Franks, (1975) *IEEE Trans. Info. Theory,* **21**, pp. 4-14, January 1975.

[2] W.A. Gardner, (1985) *SIPL-85-15 Tech. Rept., Dept. ECE, Univ. of California, Davis,* 1985.

[3] D.C. Youla, (1961) *IRE Trans. Info. Theory,* **7**, pp. 172-189, 1961.

[4] A.G. Miamee and H. Salehi, (1980) *Multivariate Analysis - V.*, pp. 167-179, 1980.

BLIND IDENTIFICATION AND EQUALIZATION VIA EXPLOITATION OF CYCLOSTATIONARITY

Lang Tong
Dept. of Elect. & Comp. Eng.
West Virginia University
Morgantown, WV

Guanghan Xu
Dept. of Elect. & Comp. Eng.
University of Texas
Austin, TX

Thomas Kailath
Information Systems Lab.
Stanford University
Stanford, CA

Blind channel identification means the identification of a certain communication channel based *solely* on the channel output. It is well-known that blind channel identification is impossible given *only* second-order statistics of stationary communication signals since the phase information of the channel response does not appear in the second-order statistics. Therefore, most blind identification techniques resort to higher-order statistics of the measurements, whose use, however, has the critical disadvantage of slow convergence. Recently we found the surprising result that if a modulated signal is oversampled, such blind identification is achievable. The fundamental reason is that the oversampled signal is no longer stationary but *cyclostationary* and the second-order statistics of a cyclostationary signal carry the phase information of the channel. By exploiting this fact we show that it is possible to identify the channel response with only the (oversampled) output data. An asymptotically exact algorithm has been developed to identify the channel response without requiring any training sequences. Simulation results illustrate good performance of the new algorithm. In addition, we also studied the blind identifiability problem and obtained identifiability conditions on channel responses.

This work was supported in part by the Joint Services Program at Stanford University (US Army, US Navy, US Air Force) under Contract DAAL03-88-C-0011, by the Army Research Office under Contract DAAL03-89-K-0109, and by grants from General Electric Company and Boeing ARGOSystems.

LINEARIZED CYCLOSTATIONARY ANALYSIS OF SPREAD SPECTRUM DIRECT-SEQUENCE CODE TRACKING PERFORMANCE IN PULSED JAMMING

Haiping Tsou, Raimundo Sampaio-Neto and Robert A. Scholtz
Communication Sciences Institute
Department of Electrical Engineering-Systems
University of Southern California
Los Angeles, CA

This paper addresses the performance analysis of direct-sequence spread spectrum pseudo-noise code tracking in the presence of cyclostationary interference. Both coherent and noncoherent code tracking are studied. For each case, the performances of two code tracking systems operating in the presence of background thermal noise and a pulsed wide-band noise jammer are presented. One system has an automatic signal-level control preceding the code tracking loop, and the other has no such signal strength protection at its front end. The pulsed jammer is modeled as a cyclostationary interferer resulting from the product of a periodic train of pulses and bandpass white noise. This new analytical approach, using a cyclostationary-process model, not only avoids the drawbacks of the conventional treatment of pulsed jamming problems, but also provides the means to directly explore the impact of the jammer's parameters, such as duty factor, repetition frequency and jamming power level, on the tracking loop's behavior. Our linearized-analysis results clearly indicate that the tracking performance, measured in terms of the tracking error variance, is a time-varying periodic function of which the peak value can reach levels far above its average if the jammer's repetition frequency is on the order of the loop bandwidth. It is also shown that the pulsed jamming effects can be effectively neutralized by automatic signal-level control if the jammer raises its peak jamming power by reducing its duty factor.

OPTICAL IMPLEMENTATIONS OF A CYCLIC SPECTRUM ANALYZER AND THE EFFECTS OF TIME COMPRESSION

Terry M. Turpin and Leslie H. Gesell
Information Systems Division
Essex Corporation
Columbia, MD

The paper presents a hybrid acousto-optic/digital processor that calculates a segment of a cross cyclic spectrum (CCS) in real time on signals with bandwidths of hundreds of megahertz. Flexibility in mapping signal parameters to processor parameters is maintained by the use of a time compression memory to match signal bandwidths to acousto-optic module bandwidths. Current photodetector technology enables parallel calculation of CCS surfaces with 1000 resolution elements in frequency and 1000 resolution elements in alpha (frequency difference). Frequency and time domain averaging are implemented in a digital module.

The calculation of the cross ambiguity function by Fourier transforming the cross cyclic spectrum in the frequency dimension is well-known. A narrow peak in the cross ambiguity function appears as a ridge in the frequency dimension in the CCS. In the cases of processing signals with large fractional bandwidth or signals at high processing gains, the ridge is not in the frequency dimension but has a slope in the frequency-alpha plane. This slope is the rate of change of time delay between the two signals in the CCS. By controlling the direction of the Fourier transform of a CCS it is easy to calculate the wide band extension of the cross ambiguity function.

The mathematics of the CCS of wide band signals where the frequency shift is frequency dependent is addressed. CCS surfaces generated by the Essex compact optical processor are presented along with hybrid processor architectures for the calculation of the wideband cross ambiguity function from an optically generated CCS.

NEW CYCLIC SPECTRAL ANALYSIS ALGORITHMS FOR REDUCING STORAGE AND SEARCH

Grace Yeung and William A. Gardner
Department of Electrical and Computer Engineering
University of California
Davis, CA

The problem of searching for weak communications and telemetry signals buried in noise is a difficult one due to computational complexity. The usual approach that exploits the property of cyclostationarity in these communications signals is to generate additive sine waves in the noisy data by putting it through a quadratic transformation, and then use exhaustive Fourier analysis (e.g., an FFT) of a very long segment of data in order to detect the signal and estimate the cycle frequencies (frequencies at which the sine waves appear.) For example, for a signal with a bandwidth of 10 MHz and an input SNR such that a data length of 0.5 seconds is required for good performance, this approach requires at least $N = 10^7$ data points to be processed for a minimum sampling rate, $1/T_s$, of 20 MHz. Hence a 10^7-point FFT needs to be computed and a search over all the frequency bins, with "bin width" equal to $1/NT_s$, is necessary for the detection of cyclic features in the signal and estimation of the corresponding cycle frequencies.

To avoid the storage of all N bins and the extensive search over all these, two new methods of detecting the signal and estimating the cycle frequencies are proposed. These two methods, namely the Autocorrelated Cyclic Autocorrelation (ACA) and Autocorrelated Cyclic Periodogram (ACP) methods, also involve the averaging over N points just as the conventional methods do, to discriminate between the sine waves and the random fluctuations that are added to it. However, they have a "bin width" (resolution in cycle frequency) that is much larger than $1/NT_s$, thereby reducing the amount of storage as well as the number of frequency bins to be searched over. This new approach cannot resolve multiple sine waves that occur within one of these wider bins, but it significantly reduces the amount of storage and search in the initial detection so that one of the conventional cyclic spectral analysis methods can be used, after initial detection, over a much narrower spectral band of width equal to that of the wider bin.

This paper begins with an overview of conventional cyclic spectral analysis, followed by mathematical formulations and analysis of the two new methods, performance comparison between the conventional and the new methods, and, finally, computer simulations that reveal both qualitative and quantitative performances of the new algorithms.

THE INSTANTANEOUS FREQUENCY OF CYCLOSTATIONARY SIGNALS: CONCEPT, PROPERTIES AND APPLICATION TO SIGNAL DETECTION

Goran D. Zivanovic
Computer Systems Design Laboratory
Belgrade, YUGOSLAVIA

This paper is concerned with the concept, periodic properties, and application to signal detection of stochastic processes that exhibit cyclostationarity (CS). The instantaneous frequency (IF) is among the basic topics in signal theory, and has been the subject of considerable study in the past for both deterministic and stochastic (mostly stationary) signals. This parameter, which has been argued to be meaningful only for narrow band signals, also plays a central role in tracking the spectral variations of nonstationary signals without assuming the narrow band condition. IF can also be viewed as a measure of the localization in time of the dominant frequency component of the signal, which is thus related to nonstationary spectrum variation. Although cyclostationary signals are of major scientific and engineering importance, it seems that most studies on IF assume generally nonstationary signals, (e.g., biological and seismic signals).

The purpose of this paper is to clarify the concept of IF for CS signals and provide the results of a study of the IF characteristic properties within the unifying framework of spectral analysis. The focus is on the periodic and almost periodic properties of IF, in both the probabilistic and statistical senses, and their relationship to the corresponding second order functions of the CS signal. The results obtained are used to derive a Cyclic Instantaneous Frequency Detector (CIFD), which has potential for outperforming the conventional IF (FM) discriminator for detection of CS signals with periodic IF.

Participants of the Workshop on Cyclostationary Signals

Mr. Eric April
Electronic Warfare Division
Defence Research Establishment
3701 Carling Avenue
Ottawa, Ontario
CANADA K1A 0K2
613/998-4821 FAX 613/990-8401
april@crow.ewd.dreo.dnd.ca

Ms. Teri L. Archer
Signal Science, Inc.
2985 Kifer Road
Santa Clara, CA 95051
408/988-2020 FAX 408/492-1442

Professor Michael E. Austin, Chair
Department of Electrical Engineering
The University of Texas
El Paso, TX 79968-0523
915/747-5470 FAX 915/747-5616

Mr. Scott P. Belanger
IBM Federal Systems Company
Route 17C
M/D 0600
Owego, NY 13827
607/751-2182 FAX 607/751-6046

Dr. John W. Betz
The MITRE Corporation, MS E025
202 Burlington Road
Bedford, MA 01730-1420
617/271-8755 FAX 617/271-2184

Dr. Nelson M. Blachman
MS 6209
Electronic Defense Laboratories
GTE Government Systems Corp.
Mountain View, CA 94039-7188
415/966-2247 FAX 415/966-3401
blachman%gtewd.dnet@gte.com

Mr. Marc Brack
Mail Drop G2113
Strategic Electronics Division
Motorola, Inc.
2501 S. Price Road
Chandler, AZ 85248-2899
602/732-3537 FAX 602/732-4034

Mr. Dale Branlund
Radix Technologies, Inc.
4020 Moorpark Avenue, Suite 212
San Jose, CA 95117
408/345-4905 FAX 408/246-4158

Dr. William A. Brown
Mission Research Corp.
2300 Garden Road, Suite 2
Monterey, CA 93940
408/372-0401

Dr. Stephen P. Bruzzone
Radix Technologies, Inc.
4020 Moorpark Avenue, Suite 212
San Jose, CA 95117
408/345-4929 FAX 408/246-4158

Mr. Daniel T. Carroll
Zeta Associates
10300 Eaton Place, Suite 500
Fairfax, VA 22030
703/385-7050 FAX 703/359-8686

Mr. Alan M. Chedester
Attn: V2
INFOSEC Expert TRANSEC Scientist
National Security Agency
Fort George G. Meade, MD 20755-6000
410/859-4707

Professor Douglas Cochran
Dept. of Electrical Engineering
Arizona State University
Tempe, AZ 85287-5706
602/965-8593 FAX 602/965-8325
cochran@enuxva.eas.asu.edu

Dr. John H. Cozzens
Circuits & Signal Processing Program
National Science Foundation
Washington, DC 20550
202/357-7853 FAX 202/357-0320

Dr. Myron Cramer
Booz, Allen & Hamilton, Inc.
4001 N. Fairfax Drive, Suite 650
Arlington, VA 22203
703/528-8080 FAX 703/525-3754

Ir. Bruce J. Currivan
atellite Terminal Operation Group
tanford Telecom
Iail Stop E5
421 Mission College Blvd.
anta Clara, CA 95056-0968
08/980-5752 FAX 408/987/5570

Ir. Amod V. Dandawate
ept. of Electrical Engineering
hornton Hall
Iniversity of Virginia
harlottesville, VA 22903-2442
04/924-3659 FAX 804/924-8818

r. Dominique Dehay
aboratoire Probabilites
Iniversite de Rennes I
ampus Beaulieu
5042 Rennes cedex
RANCE
hone: 96-37-24-04
ehay@iut-lannion.fr

r. Haluk Derin
ept. of Electrical
and Computer Engineering
Iniversity of Massachusetts
mherst, MA 01003
13/545-1526 FAX 413/545-4611

rofessor Bruce A. Eisenstein, Head
CE Department
rexel University
2nd & Chestnut Streets
hiladelphia, PA 19104
15/895-2359 FAX 215/895-1695

Ir. Robert D. Favorite, Staff Engineer
IRB Systems
.O. Box 60
cience Park
tate College, PA 16804
14/238-4311 x 2195 FAX 814/234-7720

Ir. Keith Frampton
ssex Corp.
170 Rumsey Road
olumbia, MD 21045
10/740-4789 or 4712

Professor L.E. Franks (Plenary lecturer)
Department of Electrical and
Computer Engineering
University of Massachusetts
Amherst, MA 01003
413/545-0714 FAX 413/545-4611
Professor William A. Gardner
(Workshop Chairman)
Department of Electrical and
Computer Engineering
University of California
Davis, CA 95616
916/752-1951 FAX 916/752-8428
707/944-0648 FAX 707/944-0144

Mr. Glenn Golden
Room 4F 515
AT&T Bell Laboratories
Crawfords Corner Road
Holmdel, NJ 07733
908/949-4635

Mr. Joe Harsanyi
Naval Research Laboratory
Code 9120
4555 Overlook Avenue SW
Washington, DC 20375-5000
202/767-1081

Mr. Rick Hennings
ESL, Inc.
Mail Station A1
P.O. Box 3510
Sunnyvale, CA 94088-3510
408/945-2877

Professor Melvin J. Hinich
Department of Government
University of Texas
Austin, TX 78713
512/835-3278 FAX 512/835-3259
hinich@utxvm.bitnet

Dr. Harry L. Hurd
Harry L. Hurd Associates
309 Moss Run
Raleigh, NC 27614
919/846-9227 919-676-9790

Mr. Carl Hilton Jones
6913-21 Springcreek Cove
Raleigh, NC 27613-3255
919/781-9288

Ir. Mark F. Kahn
-Systems, Inc; Greenville Div.
880 Cowell Blvd. #209
avis, CA 95616
16/753-7029 FAX 916/753-7230

rofessor Thomas Kailath
ept. of Electrical Engineering
urand 117
tanford University
tanford, CA 94305-4055
15/723-3688 FAX 415/723-8473

Is. Carolyn Koenig
ignal Science, Inc.
985 Kifer Road
anta Clara, CA 95051
08/988-2020 FAX 408/492-1442

r. John F. Kuehls
SL
RW Maryland Engineering Lab
724 Alexander Bell Drive
olumbia, MD 21046
10/290-0500 FAX 410/290-0515

rofessor B. C. Levy
ept. of Electrical
and Computer Engineering
Jniversity of California
avis, CA 95616-5294
16/752-8025 FAX 916/752-8428

rofessor Herschel H. Loomis, Jr.
ept. of Electrical Engineering
ode EC/Lm
Iaval Postgraduate School
Ionterey, CA 93943
08/646-3214

rofessor Andrzej Makagon
epartment of Statistics and Probability
Vells Hall
Iichigan State University
ast Lansing, MI 48824-1027
17/353-6369 FAX 517/336-1405

rofessor P.R. Masani
epartment of Mathematics and Statistics
Jniversity of Pittsburgh
ittsburgh, PA 15260
12/624-8378 FAX 412/624-8397
-mail: MATHSTAT@pittvms.bitnet

Professor A. G. Miamee
Dept. of Applied Mathematics
Hampton University
Hampton, VA 23668
804/727-5842 FAX 804/727-5084

Professor Joel M. Morris
Electrical Engineering Department
University of Maryland, Baltimore County
5401 Wilkens Avenue
Baltimore, MD 21228-5398
410/455-3503 FAX 410/455-3559
morris@umbc1.umbc.edu

Dr. Tokunbo Ogunfunmi
Department of Electrical Engineering
Santa Clara University
Santa Clara, CA 95053
408/554-4481 FAX 408/554-5474

Dr. A.J. Paulraj
Durand 123
Department of Electrical Engineering
Stanford University
Stanford, CA 94305-4055
415/723-3688 FAX 415/723-8473

Professor Luigi Paura
Dipartimento di Ingegneria Elettronica
Università degli Studi di Napoli
via Claudio 21
I-80125 Napoli
ITALY
+39-81-768-3150 FAX +39-81-768-3149

Professor Mohsen Pourahmadi
Division of Statistics
Northern Illinois University
Dekalb, IL 60115-2854
815/753-6799 FAX 815/753-6798
Pourahm@math.niu.edu

Professor Glenn E. Prescott
Dept. of Elect. & Comp. Eng.
University of Kansas
1013 Learned Hall
Lawrence, KS 66045
913/864-7760 FAX 913/864-7789

Dr. Bart F. Rice
Electronic Products Engineering
Lockheed Missiles & Space Co., Inc.
1111 Lockheed Way
Sunnyvale, CA 94086
408/756-4892 FAX 408/756-4175
Rice_Bart@mm.SSD.LMSC.Lockeed.com

Dr. Randy S. Roberts
Sensor Systems and Robotics Group
Group MEE-3 Mail Stop J580
Los Alamos National Laboratory
Los Alamos, NM 87545
505/665-4485 FAX 505/665-3911

Professor Sumit Roy
Dept. of Electrical Engineering
University of Pennsylvania
200 S. 33rd Street
Philadelphia, PA 19104-6390
215/898-2260 FAX 215/573-2068
roy@pender.33.upenn.edu

Mr. Stuart Sandberg
Aware, Inc.
1 Memorial Drive, 4th floor
Cambridge, MA 02142
617/225-3847 FAX 617/577-1710

Dr. Vinay Sathe
Box 500, D/S 50-370
Tektronix, Inc.
Beaverton, OR 97077
503/627-4307 FAX 503/627-5502

Professor Stephan V. Schell
(Plenary lecturer)
Department of Electrical and
Computer Engineering
Pennsylvania State University
University Park, PA 16802
814/865-7667

Dr. Michael Schildcrout
Naval Security Group,
Command Headquarters
3801 Nebraska Avenue NW
Washington, DC 20393-5210
202/282-0484 FAX 202/282-0329

Dr. Jon A. Sjogren
AFOSR/NM, Bldg. 410
Mathematical and
Information Sciences Directorate
Air Force Office of Scientific Research
Bolling AFB, DC 20744
202/767-4940 FAX 202/404-7496

Dr. Chad M. Spooner (Plenary lecturer)
Department of Electrical and
Computer Engineering
University of California
Davis, CA 95616
916/752-1326 FAX 916/752-8428

Mr. James P. Stephens
USAF WL/AAWW-2
WPAFB, OH 45433-6543
513/255-4933 FAX 513/476-4642
e-mail: STEPHENSJP%AVLAB.DNET
@AAUNIX.WL.WPAFB.AF.MIL

Mr. Bert H. Tanaka
Applied Physics Laboratory MS B-N570
The Johns Hopkins University
Johns Hopkins Road
Laurel, MD 20723-6099
301/953-6347

Dr. Haiping Tsou
Jet Propulsion Laboratory
4800 Oak Grove Drive, 238/343
Pasadena, CA 91109
818/354-2393 FAX 213/740-4449

Dr. Terry Turpin
Essex Corp.
9170 Rumsey Road
Columbia, MD 21045
410/740-4712 or 4789

Dr. Karel Vokurka
Svédská 27
466 02 Jablonec n.N.
CS-466 02
CZECHOSLOVAKIA
(0042)-428-513/372 FAX (0042)-428-23064

Dr. Harper J. Whitehouse
Naval Ocean Systems Center, Code 707
6441 Del Paso Avenue
San Diego, CA 92120
619/553-2497

Mr. Chris Wright
Advent Systems
355 Ravendale Drive
Mountain View, CA 94043
415/961-9400 FAX 415/961-8208

Professor Guanghan Xu
Dept. of Electrical and Computer Engineering
Engineering Science Building 343
University of Texas, Austin
Austin, TX 78712-1084
512/471-5909 FAX 512/471-5532

Ms. Grace Yeung
Department of Electrical and
Computer Engineering
University of California
Davis, CA 95616
916/756-6832