Editorial: Non-Rayleigh Reverberation and Clutter

I. INTRODUCTION

ACTIVE remote sensing systems transmit energy into an environment and then acquire and process the scattered energy in order to infer information about objects of interest in that environment or properties of the environment itself. In addition to energy scattered directly by objects of interest, usually termed targets, the sensing system is often hindered by interfering returns having similar character to the target echoes. When the number of interfering returns is large relative to the size of the system's resolution, the central limit theorem suggests that the measured data will follow a Gaussian probability density function (pdf), with the resulting envelope of the signal following a Rayleigh pdf. However, when the environment and sensing system are such that there are not enough independent scatterers within a resolution cell for the central limit theorem to hold, the envelope pdf can diverge from the Rayleigh pdf. This typically results in a pdf with heavier tails, leading to a higher probability of false alarm (P_{fa}) in the sensing system than when the envelope data are Rayleigh distributed. From a statistical-modeling perspective, there is a continuum from Rayleigh-distributed data through to very heavy-tailed target-like data from interfering returns. In addition to failure of the central limit theorem, there are other means by which the envelope data in an active sensing system can follow non-Rayleigh pdfs, including inhomogeneity in the environment as well as hardware and signal-processing induced effects.

Although non-Rayleigh distributions observed at the output of remote sensing systems are important in a variety of fields, we restrict ourselves in this Special Issue of the IEEE JOURNAL OF OCEANIC ENGINEERING to sonar and radar, two of the most common applications of active sensing. In active sonar systems, target-like false alarms arising from non-Rayleigh envelope data are often termed clutter while the radar community would refer to these as clutter discretes. The papers of the special issue [1]–[18] represent research spanning a wide range of topics related to the subject and are a 50% increase over the first Special Issue on this topic [19] published six years ago. In organizing the papers in the Special Issue, it is useful to consider the various areas of research related to clutter in active systems. Broadly, these areas may be described as 1) the discovery, analysis, and modeling of clutter sources in the environment; 2) physical modeling of scattering and propagation as they cause or modify clutter; 3) analysis, modeling, and simulation of clutter-dominated sonar system data; and 4) signal and information processing which induces, accounts for, or reduces clutter-derived false alarms.

The different research areas to which the papers of this Special Issue contribute are listed below. The latter two categories have been combined in the list as they are often difficult to separate. In fact, the coupled nature of the problem, where both the environmental conditions and sonar system must conspire to produce non-Rayleigh envelope data, often leads to research spanning several of these categories.

- Clutter sources:
  - — biologic [1], [2], geologic, anthropogenic;
  - — deterministic and stochastic;
  - — individual objects [1] and fields of objects [1], [2] (i.e., "micro" and "macro" modeling).
- Acoustic scattering and propagation:
  - — acoustic measurement, modeling, and analysis of clutter sources [1];
  - — effects of propagation on scatter/clutter statistics [3]–[5], [13];
  - — scattering from rough [4], [5], patchy [9], or inhomogeneous [10] surfaces and fields of discrete objects;
  - — *in situ* or remote sensing to characterize clutter (i.e., inversion).
- Sonar system and signal processing:
  - — statistical analysis of sonar-system data [6]–[9], [13], [17];
  - — phenomenological and physics-based statistical models of sonar data [9], [11];
  - — simulation of hydrophone, beam, or detection data;
  - — effects of sonar system and signal processing on clutter statistics [1], [6], [11]–[13];
  - — signal processing: estimation [14], [15], detection [15], [18], tracking [16], and classification [7], [17];
  - — sonar performance models [18].

II. THE PAPERS OF THE SPECIAL ISSUE

In this section, we briefly describe the key points of each paper as they relate to the topic of the special issue and common themes we see in current research. It is important to note that what follows is our impression of the highlights of each paper and that the papers contain additional interesting material.

With respect to real data analysis, 11 of the 18 papers analyze or present real data: five in low- or mid-frequency systems, five in high-frequency systems, and one with sea-surface radar data. The pdf models encountered in this Special Issue include: Rayleigh, K, Weibull, Rayleigh mixture, log-normal, extreme-value, generalized Pareto, gamma, exponential, Poisson–Rayleigh, power-law, Rayleigh-power-law mixture, and K–K mixture.

Stanton and Chu [1] examine the statistical distributions resulting from scattering from individual and groups of fish with data obtained from a downward-looking 2–4-kHz echosounder. Using echoes from isolated fish of similar species and size, they provide empirical evidence of the randomness induced by the fish being off the main response axis of the beamformer (i.e.,

Digital Object Identifier 10.1109/JOE.2010.2047671

the "beampattern" effect, described in detail by the authors in [12], which also appears in this Special Issue). Then, in analyzing data containing both background and fish, they illustrate the efficacy of a mixture of a Rayleigh pdf and the beampattern-induced pdf when the fish are primarily isolated (resolvable) and a two-component Rayleigh mixture when the fish are in a patch and therefore not resolvable. The beampattern effects and the multicomponent nature of the data are clear contributors to the non-Rayleighness of the resulting pdfs.

La Cour and Hamann [2] present a stochastic model for the coordinated motion of discrete biologics (e.g., a school of fish) for the purposes of active sonar simulation. The model has only six parameters: the mass of an individual, thrust, drag, grouping, arrayal, and randomization forces. The authors derive asymptotic properties of the model and illustrate how it is effective in simulating the grouping and schooling behavior of biologics observable in certain active sonar systems.

Harrison [3] explores the effect of propagation on reverberation statistics, hypothesizing that focusing during forward scattering can produce non-Rayleigh distributions. Existing Fresnel–Kirchoff theory is extended to derive scintillation index (SI) for bistatic geometries. Even weak undulations in the seafloor are seen to produce SI greater than one (i.e., envelope pdfs heavier tailed than Rayleigh), with greatest effect when the sonar's depth, or slant range for bistatic geometries, is nearly the radius of curvature of the undulations. Simulation analysis additionally confirmed the effect for Gaussian-distributed surfaces with Gaussian-shaped correlation functions. Adding an uncorrelated component forced the SI toward unity, regardless of the SI produced by the original surface.

LePage [4] evaluates the non-Rayleighness of reverberation in a shallow-water waveguide arising from scattering from rough surfaces with chi-squared-distributed height fields having arbitrary degrees of freedom, exponentially shaped correlation function, and von Karman spectra. Higher order moments of the reverberation intensity are derived using a normal-mode propagation model and first-order perturbation theory for scattering from the rough surfaces. These are then used to quantify the departure from the Rayleigh envelope pdf in terms of the SI and K-distribution shape parameter. In addition to the degree of non-Gaussianity of the surface, the non-Rayleighness in the envelope pdf is seen to be driven by the ratio of the effective ensonified area (including multipath) to the correlation length scale of the bottom roughness with small values leading to higher SI and lower K-distribution shape parameter.

Lingevitch and LePage [5] utilize parabolic equation simulation to obtain sample reverberation time series arising from rough surfaces having either Gaussian- or exponentially-distributed heights. Although forcing a Monte Carlo analysis, the parabolic-equation approach does not have the limitations imposed by the perturbation-theory analysis reported by LePage in [4]. A statistical analysis is performed on the normalized time series in terms of pdf histograms, SI, and the K-distribution shape parameter. The authors find that while Gaussian-distributed roughness yields envelope statistics close to the Rayleigh distribution, non-Gaussian roughness heights produce distributions that are heavy tailed. The SI and K-distribution shape parameter results are seen to compare favorably with moment-based predictions from the less-computationally-intensive RSNAP model.

Gavrilov and Parnum [6] present a statistical analysis of backscatter derived from data collected with a multibeam sonar system from sand and rhodolith-covered seabeds. The backscatter envelope distribution was seen to be essentially Rayleigh for the sandy bed at all incidence-angle groups while the rhodolith-covered bed presented non-Rayleigh pdfs only at the higher incidence angles, reiterating the expectation that the correlation length of the seafloor in relation to the sonar footprint drives the envelope statistics. In addition to the backscatter envelope, the authors also analyze the statistics of sidescan data and peak intensity (other processed data streams commonly found in multibeam sonar systems) with a variety of distributions including the Weibull, gamma, K, log-normal, and extreme-value distributions. Although accounting for the processing (root mean square, averages, or maximums) can indicate which distribution should be the best fit (e.g., an extreme-value distribution for the peak intensity), the impact of other effects such as the sonar beampattern is seen to lead to deviations.

Gelb, Heath, and Tipple [7] present a statistical analysis of clutter from a midfrequency active sonar system using the K and generalized Pareto (GP) distributions. The clutter is characterized as originating from bottom structures, from fields of compact fixed objects, or from compact moving objects. The statistical analysis illustrates that the non-Rayleighness of each type increases according to the order presented. While the K and GP distributions provided good fits to the first two clutter types, only the GP distribution was able to fit the highly non-Rayleigh responses from the compact moving objects. Using sample cumulants as features in a classifier, the authors then illustrate that the three clutter classes are largely, though not completely, separable.

Bareš, Evans, and Long [8] investigate the fit of the K, Weibull, and log-normal distributions to the statistics of clutter-dominated broadband active sonar data. The fit is quantified by the modified Kolmogorov–Smirnov (KS) and upper-tail Anderson–Darling (AD) tests, for which critical values accounting for parameter estimation are obtained through simulation analysis under the K and Weibull distributions. While the K and Weibull distributions are both seen to represent the data well, the K-distribution provides a better fit in the tails of the distribution. The log-normal pdf, while fitting a very high percentage of data according to the KS test, fit very little of the data ($<0.1\%$) according to the AD test, illustrating the efficacy of the AD test in evaluating the fit of a distribution in the tails compared with the KS test.

Chotiros [9] examines the reverberation envelope pdf when the environment comprises multiple sediment types; that is, patchy environments. Using the measurements and analysis of [20], the data not fit well by the K-distribution are seen to have multiple modes in the pdf formed from the three-component-Rayleigh-mixture parameters, which can degenerate into one- or two-component mixtures in a variety of ways. Interpreting the multiple modes as arising from multiple sediment types, it is argued that the pdf should be a mixture of individual pdfs representing each type. Noting that non-Rayleighness can be induced by system parameters, the author suggests a mixture of K-distributions as a model for patchy environments where a Rayleigh mixture (or K–Rayleigh mixture) would be a special case of the more general mixture. The issue of stationarity is raised where patchy environments may not fit the mathematical definitions of strict- or wide-sense stationarity, yet the composite pdf over the analysis window can be important to system performance analysis.

Lyons, Abraham, and Johnson [10] present a model to predict the impact of seafloor ripples on synthetic aperture sonar (SAS) image statistics. The quasi-periodic variation in scattering strength produced by ripple-induced changes in seafloor slope is treated as a deterministic amplitude scaling on random speckle produced by the SAS imaging process. The varying amplitude scaling is seen to make the image-level statistics heavier tailed than the speckle statistics. Good agreement is seen between the model predictions of an effective K-distribution shape parameter and that estimated from experimental data.

Cobb, Slatton, and Dobeck [11] develop a model for SAS image textures comprising a Gaussian-shaped imaging point-spread function, a K-distributed intensity distribution, and a sonar-cross-section autocorrelation function (ACF) characterized by a mixture of Gaussian pdfs. Each component in the mixture is a 2-D, zero-mean Gaussian pdf, parameterized by its frequency of occurrence, length scales in the major and minor axes, and orientation. An estimation procedure that sequentially estimates the parameters of these components is proposed and evaluated using real data examples. The flexibility of the Gaussian mixture ACF allows the model to fit a variety of textures (e.g., those from hardpack sand, seagrass, and rocky seabeds) with just a few components. However, the zero-mean restriction of the Gaussian mixture is seen to limit the ability of the model to represent the periodicity observed in rippled seafloors.

Chu and Stanton [12] derive the envelope pdf for the case of scatterers randomly displaced from the main response axis (MRA) of the sonar beam or beamformer while accounting for the beampattern-induced scalloping loss. The random placement with respect to the MRA translates into a random scale on the amplitude of each scatterer, which is approximately modeled by a power-law pdf when the displacement is uniformly random. A characteristic-function approach is used to combine the contributions from multiple scatterers, resulting in integral equations for the overall pdf. Small numbers of scatterers are seen to result in highly non-Rayleigh envelope distributions, even when the individual scatterer echoes are themselves Rayleigh distributed. As expected, increasing the number of scatterers forces the envelope pdf toward the Rayleigh distribution.

Hjelmervik [13] considers false alarms that arise in an active sonar system from nonstationarity in reverberation power levels occurring within the background estimation window in the normalizer. The phenomenon, known as false-alarm-rate inflation, results when the reverberation power level in the background estimation window is less than that in the region being normalized and can even occur when the scattering results in Rayleigh-distributed reverberation. The author derives a predictive model for the increase in the probability of false alarm and compares it with data from a low-frequency active sonar system with compelling results.

Abraham and Lyons [14] derive and evaluate approximate-Bayesian parameter estimators for the K-distribution shape parameter. As a compromise between maximum-likelihood estimators that can be computationally intensive and method-of-moments estimators that often fail to provide a solution, an approximate Bayesian formulation of the latter is developed. The resulting estimators always provide a solution and have performance and computational complexity on par with the method-of-moments estimators.

Güntürkün [15] develops a radar scene analyzer (RSA) providing probabilistic information on the measurements and target state for a Bayesian target tracker where the background clutter arising from the sea surface is the product between speckle and texture components. The proposed RSA assumes that the texture component, related to the sea-surface waves, modulates both the speckle and target return and incorporates this into the likelihood estimates produced by the RSA. Application to real data qualitatively illustrates the efficacy of the technique for weak target echoes.

Brekke, Hallingstad, and Glattetre [16] extend the probabilistic data association filter with amplitude information (PDAF-AI) used in active-sonar tracking by incorporating likelihoods accounting for estimation of the background noise power and by allowing the background to be K-distributed. In each case, the likelihoods are more conservative than the standard PDAF-AI, which assumes the background noise to have a Rayleigh-distributed envelope and power to be known. They observe that when the background is heavily cluttered, the tracker using K-distribution likelihoods outperformed the alternatives. However, when the background is less cluttered (i.e., more Rayleigh-like), accounting for the estimation of the background power is sufficient.

Fialkowski and Gauss [17] present three techniques useful in identifying and controlling clutter in active sonar systems and evaluate them on broadband, low-frequency experimental data. An analysis of the temporal persistence of threshold exceedances (i.e., the number of pings in a 7-ping span containing a detection at a specific geographic location) identified the most persistent false alarm contributors. Similar to the results of [13], many of the “persistent” false alarms were seen to be associated with the leading edges of topographic structure in the bottom, as identified by a depth-weighted slope. Finally, the power of the discrete-scatterer component in the Poisson–Rayleigh distribution was seen to provide feature information that is largely independent of the peak signal-to-noise ratio (SNR) of an echo, implying a potential for improved rejection of bottom clutter relative to target-like objects.

Abraham [18] develops approximations to the detection threshold (DT) term in the sonar equation for non-Gaussian additive backgrounds (i.e., a non-Rayleigh-distributed envelopes). The approximations use the detector threshold (which only depends on P_{fa}) derived for the non-Gaussian background, but approximate P_d by that for a Gaussian background, enabling exploitation of the Albersheim-type approximations currently used to obtain DT for Gaussian backgrounds. The accuracy for both K- and Weibull-distributed backgrounds is better than one tenth of a decibel for fluctuating targets, while a correction factor is required to achieve accuracy on the order of one tenth of a decibel for nonfluctuating targets.

III. SUMMARY

The coupling between environmental conditions, system characteristics, and signal processing in defining non-Rayleigh pdfs in active sensing systems leads to multidisciplinary research, as evidenced by the papers in this Special Issue. Several common themes surface from the research presented in [1]–[18]. While a descriptive statistical analysis of sonar data continues to aid the discovery process, it is encouraging and indicative of growth in our knowledge base to see research evaluating the impact of specific environmental processes (e.g., propagation and scattering) and signal processing (e.g., beamforming or normalization) on clutter statistics, especially with the increasing number of model-data comparisons. Inhomogeneity in the environment (e.g., patches, ripples, or isolated individual scatterers) is gaining ground as a common cause of non-Rayleigh pdfs in active sensing systems. Interestingly, physical processes (e.g., propagation) and signal processing (e.g., beamforming and normalization) are seen to be capable of producing non-Rayleigh pdfs even when the underlying processes have Gaussian- or Rayleigh-distributed inputs. The large number of possible clutter sources appears to be leading to the development of pdf models for specific situations (e.g., the "beampattern" pdf, the K–K mixture, texture models for SAS). Finally, the use of non-Rayleigh pdfs in signal and information processing algorithms and sonar performance modeling is increasing, leading to improved system performance and performance prediction in clutter-dominated operating environments.

While significant progress has been made in identifying, characterizing, and accounting for clutter in active sonar systems over the past six years, it is clear that the field is still in its infancy. There are many areas where our understanding of the physical processes is weak, where data are lacking, or where more coupled, end-to-end models or algorithms might be developed.

ACKNOWLEDGMENT

We would like to thank the authors for their contributions and efforts in revising their manuscripts and all of the reviewers whose careful review significantly improved the quality of this Special Issue. We would also like to thank A. Lim for her help in pulling this Special Issue together and W. Carey and J. Buck for their assistance in the review process. Finally, we thank the Editor-in-Chief C. de Moustier for the opportunity to guest edit this Special Issue.

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