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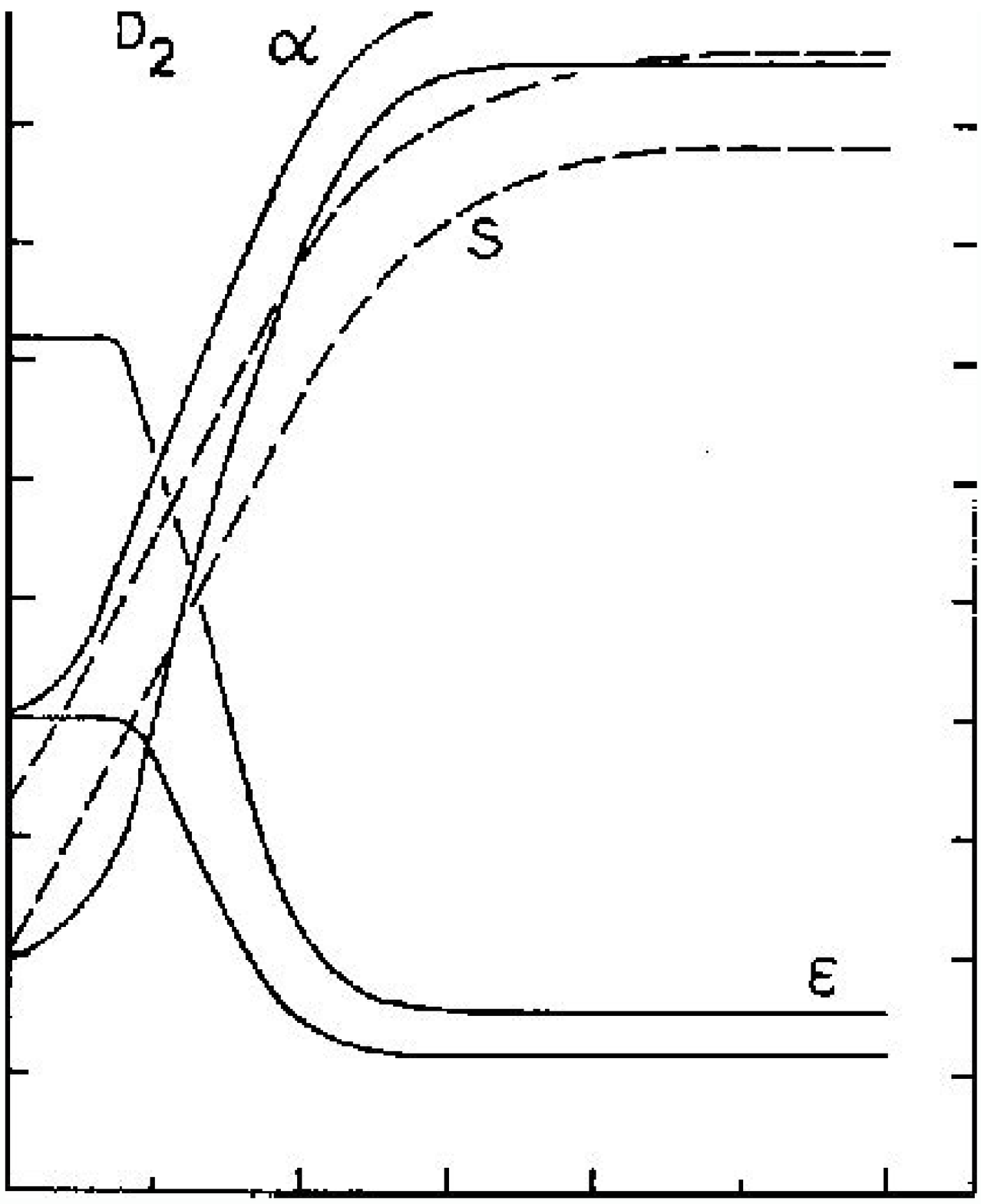

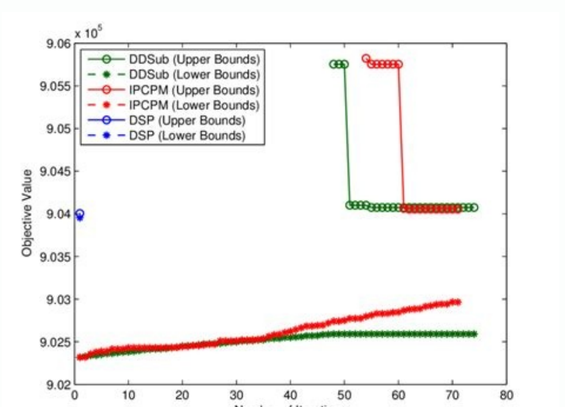

Statistics of the MLE and Approximate Upper and Lower Bounds – Part 2: Threshold Computation and Optimal Signal Design

Achraf Mallat, *Member, IEEE,* Sinan Gezici, *Senior Member, IEEE,* Davide Dardari, *Senior Member, IEEE,* and Luc Vandendorpe, *Fellow, IEEE*

***Abstract*—Threshold and ambiguity phenomena are studied in Part 1 of this work Mallat et al. where approximations for the mean-squared-error (MSE) of the maximum likelihood estimator are proposed using the method of interval estimation (MIE), and where approximate upper and lower bounds are derived. In this part we consider time-of-arrival estimation and we employ the MIE to derive closed-form expressions of the begin-ambiguity, end-ambiguity and asymptotic signal-to-noise ratio (SNR) thresholds with respect to some features of the transmitted signal. Both baseband and passband pulses are considered. We prove that the begin-ambiguity threshold depends only on the shape of the envelope of the ACR, whereas the end-ambiguity and asymptotic thresholds only on the shape of the ACR. We exploit the results on the begin-ambiguity and asymptotic thresholds to optimize, with respect to the available SNR, the pulse that achieves the minimum attainable MSE. The results of this paper are valid for various estimation problems.**

***Index Terms*—Nonlinear estimation, threshold and ambiguity phenomena, maximum likelihood estimator, mean-squared-error, signal-to-noise ratio, time-of-arrival, optimal signal design.**

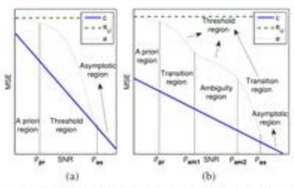

Figure 1. SNR regions (a) *A priori*, threshold and asymptotic regions for non-oscillating ACR (b) *A priori*, ambiguity and asymptotic regions for oscillating ACR (c: CRLB, ϵ_U: MSE of uniform distribution in the *a priori* domain, ϵ: achievable MSE, ρ_{pr}, ρ_{am1}, ρ_{am2}, ρ_{as}: *a priori*, begin-ambiguity, end-ambiguity and asymptotic thresholds).

I. Introduction

NONLINEAR deterministic parameter estimation is subject to the threshold effect Ziv and Zakai [1969], Chow and Schultheiss [1981], Weiss and Weinstein [1983], Weinstein and Weiss [1984], Zeira and Schultheiss [1993, 1994], Sadler and Kozick [2006], Sadler et al. [2007]. Due to this effect the signal-to-noise ratio (SNR) axis can be split into three regions as illustrated in Fig. 1(a):

1) *A priori* region: Region in which the estimator becomes uniformly distributed in the *a priori* domain.
2) Threshold region: Region of transition between the *a priori* and asymptotic regions.
3) Asymptotic region: Region in which an asymptotically efficient estimator, such as the maximum likelihood estimator (MLE), achieves the Cramer-Rao lower bound (CRLB). Otherwise, the estimator achieves its own asymptotic mean-squared-error (MSE) (e.g. MLE with random signals and finite snapshots Renaux et al. [2006, 2007]).

When the autocorrelation (ACR) with respect to (w.r.t.) the unknown parameter is oscillating, five regions can be identified as shown in Fig. 1(b): 1) the *a priori* region, 2) the *a priori*-ambiguity transition region, 3) the ambiguity region, 4) the ambiguity-asymptotic transition region, and 5) the asymptotic region. The MSE achieved in the ambiguity region is approximately equal to the envelope CRLB (ECRLB). In Figs. 1(a) and 1(b), ρ_{pr}, ρ_{am1}, ρ_{am2} and ρ_{as}, respectively, denote the *a priori*, begin-ambiguity, end-ambiguity and asymptotic thresholds determining the limits of the defined regions.

As the evaluation of the statistics of most estimators such as the MLE is often unattainable in the threshold region, many lower bounds have been proposed Van Trees and Bell [2007], Renaux [2006] for both deterministic (the unknown parameter has only one possible value) and Bayesian (the unknown parameter follows a given *a priori* distribution) estimation in order to be used as benchmarks and to describe the behavior of an estimator in that region.

Threshold computation is considered in Weiss and Weinstein [1983], Weinstein and Weiss [1984] where the *a priori*, begin-ambiguity, end-ambiguity and asymptotic thresholds are computed based on the Ziv-Zakai lower bound (ZZLB); the ZZLB evaluates accurately the asymptotic threshold and detects roughly the ambiguity

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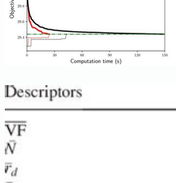

Descriptors	Lower bound	Upper bound
$\overline{\text{VF}}$	0.1	0.3
$\bar{N}$	100	300
$\bar{r}_d$	5	30
$\bar{e}_l$	1	3

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In: probability in a space of banach. Progress in probability, vol. 8, pages 39 - 54. Birkhã £ User, Basel (1992) Google Scholarã ¢ Heragrand, m.: Corresponding theorems and discrepancy calculations using greaterization measures. Marmalade. Mathematics. SOC. 7, 455An Â tow â € œ537 (1994) Crossrefã ¢ Mathscinet ã ¢ Google Scholar ã ¢, M., Yukich, J.: The integration of the cost of the exponential transport square. Ann. App. Probab. 3, 1100ã ¢ â,¬ â € œ1111 (1993) Crossrefã ¢ Mathscinet ã ¢ Google Scholar Yukich, J.: Some generalizations of the two -sampled Euclidean combination problem. In: probability in the spaces of Banach, vol. 8, Brunswick, Me, 1991. Program. Probab., Vol. 30, pages 55 - 66. Birkh bets, Boston (1992) Google Scholar Numpy and Scipy provide a complete means to work with 2D data. Pandas has the specific class data frame to manage 2D labeled data. Start creating an array number 2D: >>>>> a = np.array ([[1, 1, 1], ... [2, 3, 1], ... [4, 9, 2] ,. .. [8, 27, 4], ... [16, 1, 1]) >>> An array ([[1, 1, 1], [2, 3, 1], [4, 9, 2], [8, 27, 4], [16, 1, 1]) Now you have a 2D data set, which you will use in this section. It is possible to apply the functions and methods of Python statistics, just as you would do for 1D data: >>>>>> np.mean (a) 5.4 >>> A.Mean () 5.4 >>> np.median (a) 2.0 >>> A.Var (ddof = 1) 53.400000000001 As you can see, statistics are obtained (such as average, median or variance) on all data in array a. Sometimes, this behavior is what you want, but in some cases, you will want to calculate these quantities for each line or column of your 2D array. The functions and methods you have used so far have an optional parameter called Axis, which is essential to manage 2D data. The axis can take one of the following values: axis = nobody says to calculate the statistics above all data in the array. The above examples work this way. This is what this is about. is often the default in NumPy. axis=0 says to calculate the statistics across all rows, that is, for each column of the array. This behavior is often the default for SciPy statistical functions. axis=1 says to calculate the statistics across all columns, that is, for each row of the array. Let¢ÃÂÂs see axis=0 in action with np.mean(): >>>>>> np.mean(a, axis=0) array([6.2, 8.2, 1.8]) >>> a.mean(axis=0) array([6.2, 8.2, 1.8]) The two statements above return new NumPy arrays with

the mean for each column of a. In this example, the mean of the first column is 6.2. The second column has the mean 8.2, while the third has 1.8. If you provide axis=1 to mean(), then you¢ÃÂÂll get the results for each row: >>>>>> np.mean(a, axis=1) array([1., 2., 5., 13., 6.]) >>> a.mean(axis=1) array([1., 2., 5., 13., 6.]) As you can see, the first row of a has the mean 1.0, the second 2.0, and so on. Note: You can extend these rules to multi-dimensional arrays, but that¢ÃÂÂs beyond the scope of this tutorial. Feel free to dive into this topic on your own! The parameter axis works the same way with other NumPy functions and methods: >>>>>> np.median(a, axis=0) array([4., 3., 1.]) >>> np.median(a, axis=1) array([1., 2., 4., 8., 1.]) >>> a.var(axis=0, ddof=1) array([37.2, 121.2, 1.7]) >>> a.var(axis=1, ddof=1) array([0., 1., 13., 151., 75.]) You¢ÃÂÂve got the medians and sample variations for all columns (axis=0) and rows (axis=1) of the array a. This is very similar when you work with SciPy statistics functions. But remember that in this case, the default value for axis is 0: >>>>>> scipy.stats.gmean(a) # Default: axis=0 array([4. , 3.73719282, 1.51571657]) >>> scipy.stats.gmean(a, axis=0) array([4. , 3.73719282, 1.51571657]) If you omit axis or provide axis=0, then you¢ÃÂÂll get the result across all rows, that is, for each column. For example, the first column of a has a geometric mean of 4.0, and so on. 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Sometimes, you might want to use a DataFrame as a NumPy array and apply some features to it. You can get all data from a DataFrame with .values or .to_numpy(): > > > df.values array([1, 1, 1], [2, 3, 1], [4, 9, 2], [8, 27, 4], [16, 1, 1]]]] df.to_numpy() array([1, 1, 1], [2, 3, 1], [4, 9, 2], array [8, 27, 4], [16, 1] Note that df.to_numpy() is more flexible because you can specify the type of data and if you want to use the existing data or copy it. As a series, DataFrame objects have the .describi() method that returns another DataFrame with the summary of statistics for all columns: >>>>>>> > > df.describe() Account B C 5.00000 5.000.000.000 5.000.000 5.000.000.000.000 medium 6.20000 8.200000 1.80000 m. 6.09918 11.009087 1.30384 min 1.000.000 1.000.000 The summary contains the following results: count: the number of elements in each column means: the medium of each column md: the standard deviation min and max: the minimum values and maximum 25%, 50% and 75%: the per centilei If you want the resulting DataFrame object to contain other per centiles, then you should specify the value of the optional parameter per centiles. You can access each element of the summary such as this: >>>> > df.describe().at['mean', 'A'] 6.2 > df.describe().at['50%', 'B' 3.0 This is how you can get Python statistics descriptive in a Series object with a single call Pandas method. Call.

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